LAKE AND WATERSHED NEUTRALIZATION STRATEGIES

D. B. Porcella[1], C. T. Driscoll[2], C. L. Schofield[3], and R. M. Newton[4]

[1]Electric Power Research Institute, Palo Alta CA USA; [2]Syracuse University, Syracuse NY USA;
[3]Cornell University, Ithaca NY USA; [4]Smith College, Northampton MA USA.

Abstract. The Experimental Watershed Liming Study (EWLS) evaluated the application of $CaCO_3$, to a forested watershed to mitigate the acidification of surface water. During October 1989, 6.9 Mg $CaCO_3$/ha was applied by helicopter to two subcatchments of about 50% (102.5 ha) of the Woods Lake watershed area. The EWLS team investigated the response to treatment of soils (chemistry and microbial processes), vegetation, wetland, stream and lake waters, and phytoplankton and fish, and applied the Integrated Lake Watershed Acidification (ILWAS) model in predicting a watershed treatment duration of up to 50 years. Observations showed a gradual change in pH, acid neutralizing capacity (ANC) and Ca^{2+} in the water column; direct lake additions of $CaCO_3$ (three different times) were characterized by abrupt changes following base addition and subsequent rapid reacidification. Moreover, the watershed treatment eliminated the snowmelt acidification of the near-shore region of the lake observed during direct lake treatments. Positive ANC water in the tributary and near-shore area improved conditions for fish reproduction and for a viable fish population. Budgets for 12-month periods before and after the watershed treatment showed that the lake shifted from a source of ANC to a sink due to retention of elevated inputs of Ca^{2+} from the watershed $CaCO_3$ application.

Key Words: acidification, acid neutralizing capacity, calcite, fish, liming, mitigation, ecosystems.

1. Introduction

Base addition ('liming') for mitigation of acidity in aquatic and terrestrial ecosystems has been practiced since Roman times (Porcella et al. 1989, Brocksen et al. 1992, Henrikson and Brodin 1995). In 1984, we began assessment of liming options in Woods Lake in the Adirondack Mountains, NY, USA, using a series of direct lake liming treatments, followed by a watershed liming. In addition, a 3-year study of acidic deposition biogeochemistry led to development of the ILWAS model (Gherini et al. 1995). These field studies enhanced understanding processes of acidification in watershed ecosystems, as well as liming and its duration. We studied watershed liming based on hydrology: precipitation onto the lake and the upland parts of the catchment, flow through soil and surface zones into Woods Lake, and outflow into the downstream drainage (Fig. 1; similarly, see e. g., Traan et al. 1995; Dalziel, et al. 1994).

The Woods Lake watershed has a total area of 208 ha (Driscoll et al. 1995), with the lake at an elevation of 606 m and watershed boundaries up to 728 m. The lake is dimictic and has a mean residence time of six months, but the small (23 ha), shallow (mean depth of 3.5 m, maximum depth of 12 m) lake has extreme variation in flow-through magnified by short-circuiting due to density differences especially during spring snowmelt after the six-month winter ice-cover. Annual precipitation ranged between 110-140 cm. The watershed has 98 percent forest cover, dominated by mature, second growth of red maple, American beech, yellow birch, and red spruce after previous harvest of the forest. Soils are young (<12,000 years) and thin (in one area in the main subcatchment up to 10 m to

Water, Air and Soil Pollution **85**: 889–894, 1995.

bedrock, but mostly 1-2 m or less). Wetlands occur around the eastern lake margins, and are associated with a large beaver pond in the main tributary. Subsurface inputs to the lake contribute about 31-38 percent of total inflow.

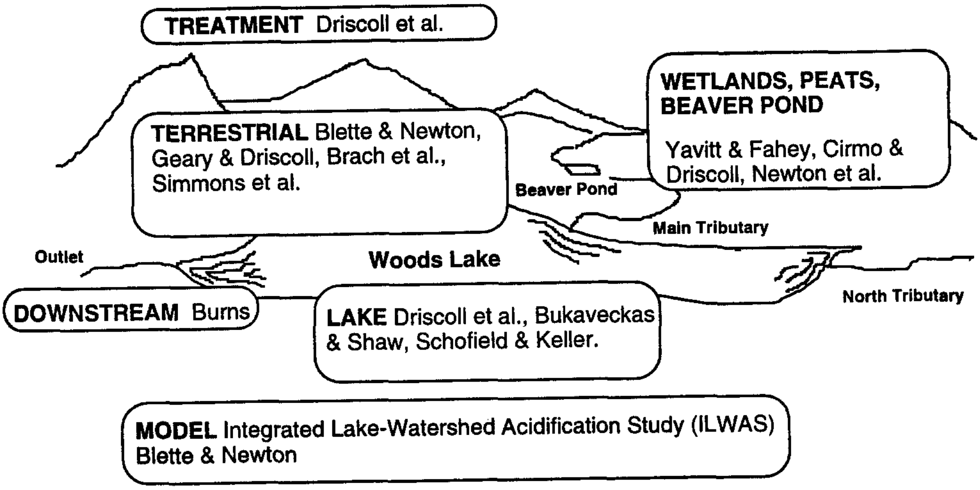

Figure 1. Schematic of Experimental Watershed Lake Study (EWLS)- (based on Driscoll et al. 1995).

We treated Woods Lake by successive helicopter additions of finely ground limestone (Tab. 1). Almost all of the limestone was calcite ($CaCO_3$) in the first two treatments, but the limestone used in the watershed (WS) treatment was 82 percent $CaCO_3$. Particle size varied with the objectives of the treatment; in the first treatment of the water column (WC) fine particles were used, but in the latter two treatments larger particles were added to settle to the bottom of the lake to create a sediment reservoir of neutralizing capacity (WC/S) or pelletized with organic binder to penetrate tree cover (WS). The areas treated were the whole lake surface for the water column treatments, and two sub-catchments (main and north tributaries) of the watershed comprising 102.5 ha or about 50 percent of the watershed area. The maintenance liming, applied by boat, helped fish to overwinter prior to the watershed treatment. The coefficient of variation for helicopter limestone delivery to soil surfaces was high, being 62 percent.

2. Results

Driscoll et al. (1995) calculated constituent mass balances and retention coefficients for Woods Lake for each treatment, and showed that the watershed-to-lake flux of Al, nitrate, and dissolved silica were altered by watershed liming. Calcium, base cations (BC), dissolved organic carbon (DOC), and ammonium values show important differences between the treatments (Tab. 2). Prior to any treatment, Ca^{2+} and BC were essentially in balance, while DOC was retained (metabolized or sedimented) and NH_4^+ was produced (ammonification). As expected for the BC, only Ca^{2+} showed responses to treatments, and BC balances were dominated by Ca^{2+}. After direct lake treatments, Ca^{2+} was strongly retained in the sediments. During the interval between direct treatments and watershed liming, Ca^{2+} inputs to Woods Lake returned to pre-treatment levels, while outputs were somewhat elevated because of continued release of Ca^{2+} from the sediments. After the lake treatments, DOC and NH_4^+ came closer to balancing, with DOC having increased output and NH_4^+ having decreased output.

Table 1. Treatments of Woods Lake with Limestone (from Porcella, 1991; Driscoll et al. 1995).

Description	Date	Limestone Added* Tons	Limestone Added* kg/ha	Ca^{++} Added Keq/ha
Water Column (WC)	May 1985	23	1000	20
Water Column/Sediment (WC/S)	September 1986	34.3	1500	30 (17 to WC; 13 to Sediments)
Water Column (Maintenance Dose, MD)	October 1988	2	87	1.7
Watershed (treated area) (WS)	October 1989	840	6890 as $CaCO_3$	344

*WC-Calcite: 71% slurry with mean particle = 2 μm; WC/S-Calcite: 19.9 tons of fine (6-44μm) and 14.4 tons of coarse particles (40-400μm); WS- 840 (nominally 1100) tons of pelletized limestone (82% $CaCO_3$, 8% $MgCO_3$, 4% organic binder; 6% unreactive) particles of 1.41-4 mm applied to 102.5 ha. All treatments by helicopter except 1988 where calcite was added by boat. 1 ton = 1000kg.

Table 2. One-year Ion Balances for Woods Lake Before and After Different Limestone Treatments*
(From Driscoll et al. 1995)

	Ca^{2+}, keq/ha-yr			BC, keq/ha-yr			DOC, kM/ha-yr			NH_4^+keq/ha-yr		
Time Period	In	Out	RC	In	Out	RC	In	Out	RC	In	Out	RC
1. pre-WC	4.6	5.0	-0.08	7.9	8.2	-0.04	23.8	15.6	0.35	0.42	0.61	-0.46
2. post-WC	24.1	19.8	0.19	27.8	23.4	0.16	22.0	19.9	0.10	0.47	0.54	-0.15
3. post-WC/S	34.3	21.4	0.38	38.1	24.9	0.35	25.9	20.8	0.20	0.47	0.51	-0.08
4. pre-WS (+MD)	9.9	10.0	-0.79	10.2	14.0	-0.37	23.6	18.5	0.22	0.48	0.22	0.53
5. post-WS	25.2	18.7	0.26	30.5	23.1	0.24	31.7	25.4	0.20	0.90	0.46	0.49

* In = wet and dry deposition plus direct lake treatments plus tributory inflow; Out = lake outflow; RC = 1 - (out/in); + is retained; - is released. BC = base cations; DOC= dissolved organic carbon.

1. June 84-May 85 2. June 85-May 86 3. October 86-September 87 4. October 88-Sepember 89 5. October 89-September 90

After watershed liming (Tab. 2), Ca^{2+} shifted back to retention, again exchanging with sediment cations. The additional Ca^{2+} input for the first year amounted to about 4 percent of the watershed treatment with Ca^{2+} . BC constituents did not increase other than Ca^{2+}, even though the added limestone contained magnesium. DOC continued to be retained, but supply from the watershed increased by about one-third. Ammonium input doubled while ouput remained fairly constant except for the interval prior to the watershed treatment; NH_4^+ shifted from loss to retention. The watershed liming increased DOC and ammonium input to the lake suggesting increased watershed decomposition of organic matter. Other constituents, Al flux, nitrate, and dissoved silica, were affected by watershed liming, also (Driscoll et al. 1995).

Blette and Newton (1995) used the ILWAS watershed simulation model to assess the duration of watershed liming benefits basedon water chemistry. Their results suggest that water quality would remain suitable for fish for up to 50 years. The model simulations confirmed measured values. However, the spatial aggregation of ILWAS (and other models) precludes one-for-one confirmation of highly varying systems having short duration events and great spatial complexity.

The key to assessing the effects of acidity mitigation in lakes and streams depends on biotic responses to liming. Fish, being at the top of the aquatic food web, provide the most sensitive indicator of the effectiveness of liming, but are affected by many habitat and community processes that may confound interpretation of the biologic effects of water chemistry. Results of fish experiments conducted by stocking the previously fishless lake (Schofield et al. 1991) with brook trout (*Salvelinus fontinalus*), showed that reproductive success was enhanced by watershed liming. The treatment improved tributary spawning habitat in the main but not the north subcatchment. Recruitment of young trout was greatly reduced by summer mortality resulting from predation. Higher reproduction and/or enhanced refugia for young trout could increase recruitment. Four year classes were present in 1993 (Schofield and Keleher 1995), and survival and fish size varied with year class, increasing with older fish (Table 3). Moreover, ecologic factors affected fish size, since earlier stockings had larger fish because previously untapped food resources were available to these fish. Measured condition factors support this conclusion (Schofield et al. 1991).

Table 3. Ecological Interactions Affect Fish Response to Liming (from Schofield and Kelleher 1995).

Year Class	Percent Survival
0+ to 1+	16-24
1+ to 2+	37-57
	Fish Size (g)
0+	22-38
1	72-112
1+	152-250
2	216-480*
2+	276-634*

*** Early stockings resulted in larger fish.**

We ascribe several reasons for successful tributary spawning. Till in the main subcatchment (up to 10 m thick) shoreline provides upwelling groundwater for egg development plus better water quality. In the north subcatchment, till is 1-2 m thick, and has little upwelling and provides less neutralization. Moreover, the presence of a beaver pond in the main but not the north tributary appeared to increase the initial neutralization (Newton et al. 1995; Cirmo and Driscoll 1995). Thus, the failure of brook trout to spawn in the north tributary was caused both by biologic factors (spawning area) as well as chemical factors, such as, lower pH (Fig. 2) (Newton et al. 1995; Schofield and Keleher 1995). Although pH values varied mostly in parallel, pH in the main tributary was higher than the north (regression: $\text{north}_{pH} = 0.56 * \text{main}_{pH} + 1.8$, $r^2 = 0.83$). Marked changes in pH

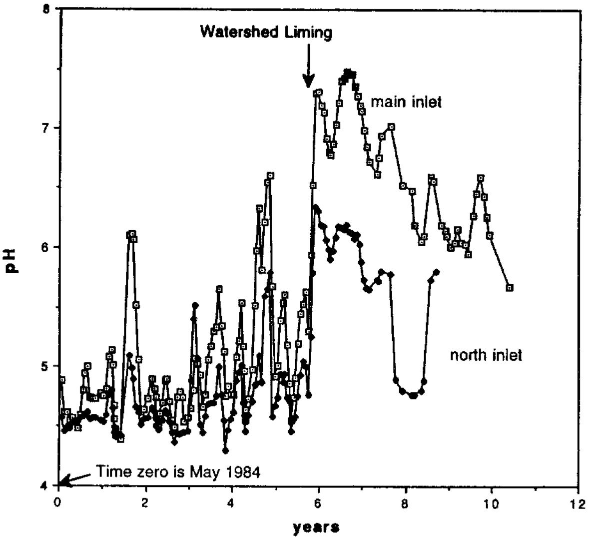

Fig. 2. Time series of pH (3-sample moving average) for two major inlets to Woods Lake, NY, USA

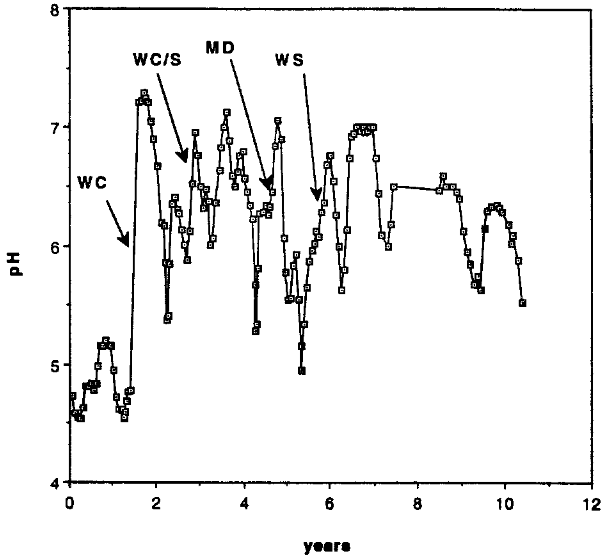

Fig. 3. As a measure of lake surface layer pH, the outlet pH (3-sample moving average) shows rapid response to liming (abbreviations as in Tab. 1).

occurred following storms, supporting the occurrence of similar patterns but quantitatively different loadings and processes in the streams. Furthermore, snowmelt acidity decreased pH below 5 in the north inlet, restricting fish use of the stream.

A different pattern is shown for the outlet - a measure of pH in the lake surface layer (Fig. 3). Ongoing monitoring (through May 1994) shows that liming increased pH in the lake surface layer, where lowest pH occurs, well above the pH 5 level. However, the lake responded not only to liming, but to the hydrologic events that show marked increases in pH shown in Fig. 2. The effects of watershed liming on lake pH showed a pattern of much higher pH and less marked pH depressions.

4. Conclusions

Dynamics of chemical constituents changed with all liming treatments. Watershed treatment changed the retention of Ca^{2+}, DOC, and NH_4^+ by altering processes in the watershed and the lake. The duration of watershed treatment greatly exceeded the duration of direct lake treatments; ILWAS model projected a duration of up to 50 years. Unlike direct lake treatments that continued to require stocking, fish recruitment to lake populations resulted from natural reproduction within the main tributary after watershed treatment. The watershed liming corrected acidic conditions in the main tributary subcatchment; biological and chemical factors affected fish recruitment. Ecologic factors appeared to limit fish growth, size, and condition. Differences between the two limed tributaries appeared to explain why fish used only one of the tributaries; till thickness and a beaver pond were the two major factors.

Acknowledgments

Work supported by the Electric Power Research Institute, Empire State Electric Energy Research Corporation, Living Lakes, Inc., U. S. Geological Survey, and U. S. Fish and Wildlife Service. We thank two anonymous reviewers for their excellent help.

References

Blette, V. L. and R. M. Newton. 1995b. Application of the Integrated Lake-Watershed Acidification Study model to watershed liming at Woods Lake, NY. Biogeochemistry. In Press.

Brocksen, R. W., et al.. 1992. Practical Guide to Managing Acidic Surface Waters and Their Fisheries. Lewis Publ., Chelsea, MI, USA. 190 p.

Cirmo, C. P. and C. T. Driscoll. 1995. The impacts of watershed $CaCO_3$ treatment on stream and wetland biogeochemistry in the Adirondack Mountains. Biogeochemistry. In Press.

Dalziel, T. R. K., E. J. Wilson, and M. V. Procter. 1994. The effectiveness of catchment liming in restoring acid waters at Loch fleet, Calloway, Scotland. Forest Ecol. Mange. 68:107-117.

Driscoll, C. T., et al. 1995. The experimental watershed liming study (EWLS): comparison of lake and watershed neutralization stretegies. Biogeochemistry. In Press.

Gherini, S. A., et al. 1985. The ILWAS model: Formulation and application. 26:425-459.

Henrikson, L. and Y. W. Brodin. 1995. Liming of Acidified Surface Waters. A Swedish Synthesis. Springer-Verlag, Berlin, Germany. 458 p.

Newton, R. M., D. A. Burns, D. A. Blette, and C. T. Driscoll. 1995. Effect of whole catchment liming on the episodic acidification of two Adirondack streams. Biogeochemistry. In Press.

Porcella , D. B. et al. 1989. Mitigation of Acidic Conditions in Lakes and Streams. In Vol. 4. Acid Precipitation - Environ. Aspects (editors, Norton, S. A. et al.) Springer-Verlag, NY. pp. 159-186.

Schofield, C. L. and C. Keleher. 1995. Comparison of brook trout reproductive success and recruitment in an acidic Adirondack lake following whole lake liming and watershed liming. Biogeochemistry. In Press.

Schofield, C. L. et al. 1991. Population dynamics of brook trout (*Salvelinus fontinalis*) during maintenance liming of an acidic lake. Water, Air, Soil Pollut. 59:41-53

Traan, T. S., T. Frogner, A. Hindar, E. Kleiven, A. Lande, and R. F. Wright. 1995. Whole-catchment liming at Tjonnstrond, Norway: an 11-year record. This Conference.