Whole Lake Chemical Additions in the Experimental Lakes Area. 1969-1983

D.R. Cruikshank

Western Region
Department of Fisheries and Oceans
Winnipeg, Manitoba R3T 2N6

April 1984

Canadian Data Report of Fisheries and Aquatic Sciences No. 449

Fisheries and Oceans Pêches et Océans

Canada

Canadian Data Report of Fisheries and Aquatic Sciences

Rapport statistique canadien des sciences halieutiques et aquatiques

Canadian Data Report of

Fisheries and Aquatic Sciences 449

April 1984

WHOLE LAKE CHEMICAL ADDITIONS IN THE EXPERIMENTAL LAKES AREA. 1969-1983

by

D.R. Cruikshank

Western Region

Department of Fisheries and Oceans

Winnipeg, Manitoba R3T 2N6

This is the 63rd Data Report

from the Western Region, Winnipeg

Cat. no. FS 97-13/449 ISSN 0706-6465

Correct citation for this publication is:

Cruikshank, D.R. 1984. Whole lake chemical additions in the Experimental Lakes Area. 1969-1983. Can. Data Rep. Fish. Aquat. Sci. 449: iv + 23 p.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

ABSTRACT

Cruikshank, D.R. 1984. Whole lake chemical additions in the Experimental Lakes Area. 1969-1983. Can. Data Rep. Fish. Aquat. Sci. 449: iv + 23 p.

Whole lake manipulations involving chemical additions simulating lake eutrophication and acidification in Experimental Lakes Area lakes have been conducted since 1969. Fertilization of lakes 226, 227, 230, 261, 302, 303 and 304 occurred from 1969 to 1980. The nutrients nitrogen, phosphorus and carbon were added in various ratios and combinations. Acidification using sulfuric acid has been conducted in three lakes (L114, L223, L302S) and with nitric acid in L302N. This data report outlines the quantities and methods used at ELA.

Key words: manipulations; acidification; fertilization

RESUME

Cruikshank, D.R. 1984. Whole lake chemical additions in the Experimental Lakes Area. 1969-1983. Can. Data Rep. Fish. Aquat. Sci. 449: iv + 23 p.

Depuis 1969, on a manipulé des lacs entiers en versant des produits chimiques dans certains lacs de la région des Lacs expérimentaux pour en simuler l'eutrophisation et l'acidification. De 1969 à 1980, on a procédé à la fertilisation des lacs 226, 227, 230, 261, 302, 303 et 304, en y ajoutant diverses quantités et combinaisons d'éléments nutritifs, notamment de l'azote, du phosphore et du carbone. Trois lacs (L114, L223 et L302S) ont été acidifiés à l'aide d'acide sulfurique et un (L302N) à l'aide d'acide nitrique. Ce rapport donne les quantités et les méthodes utilisées dans la région des Lacs expérimentaux.

Mots clés: manipulation; acidification; fertilisation

INTRODUCTION

Whole lake manipulations have been conducted at the Experimental Lakes Area since 1969 beginning with the L227 eutrophication experiment.

The acidification of L223 was designed to monitor the changes in a lake's water chemistry and aquatic life as it becomes acidic (Schindler et al. 1980; Schindler and Turner 1982). The target pH for each year was 6.0 for 1977, 5.85 for 1978, 5.50 for 1979, 5.25 for 1980 and 5.00 for 1981-83. Acid was added as needed (Table 2, Appendix 1) to maintain the target pH. Several large additions were made in early May as soon as the ice cover melted. These large additions were required to bring the pH down to its target pH. Throughout the open water season 1-3 smaller additions were made each week to maintain the epilimnion around its target pH. The mean time-weighted pH was up to 0.4 pH units greater than the target pH.

The additions of nitrogen, phosphorus and carbon to L226NE, and nitrogen and carbon to L226SW determined that phosphorus was the limiting nutrient in lake eutrophication (Schindler 1977). Levels of eutrophication were studied using various nitrogen to phosphorus ratios. The input of N:P in various ratios to the level of eutrophication was studied in lakes 227, 226, 303 and 304. Nitrogen fixation by blue-green algae occurred in N:P ratios of less than 15:1 (Flett et al. 1980; Levine, Ph.D. thesis).

In L302N, nutrients were injected into the hypolimnion below the thermocline (Schindler et al. 1980). The thermocline acted as an effective barrier with nutrients being confined largely to the hypolimnion. During 1979 and 1980 mixing between the basins occurred. In June, 1981 a curtain was installed separating the basins again. Water chemistry comparisons were done between the basins for one year. In 1982, the acidification experiment that is in progress was designed to determine the effects of nitric acid, a major component of acid rain and little studied in lakes in comparison to sulfuric acid. The experiment is designed so that the same amount of H^+ ion is added to each basin. Enough sulfuric acid is added to L302S to achieve its target pH. Nitric acid is then added to L302N in quantities that give the north basin the same input of H^+ ion as the south. This calculation also takes into account the epilimnion volume differences between the basins.

In the L230 experiment nitrogen and phosphorus were added under the ice in the same ratios as L227. It showed that an algal bloom would result prior to spring overturn (Schindler unpublished data).

The addition of phosphorus only to L261 was an attempt to determine if phosphorus alone would eutrophy a lake. It resulted in no change in primary productivity (Fee 1979).

This data report details the fertilizer and acid additions made to ELA lakes to date.

METHODS OF ADDITION

Fertilizer additions were made using three methods: "Boat Method", "Barrel Method" and the "Raft Method". The "boat method" was used from 1969 to 1974 and the "barrel method" from 1974 to 1983. The "raft method" was used only in the L302N hypolimnetic nutrient injection experiment.

Acid additions were made using two methods. The "prop-wash mix method" was used from 1976 to 1978; and from 1979 to present, the "prop-tube mix method" has been employed.

"Boat Method"

The chemicals were placed directly in a 3-m fiberglass boat which was powered by a 9.5 hp motor. The drain plug in the transom was then removed until the boat became one-third filled with water. The contents were stirred until the chemicals were dissolved. With the plug removed, the boat was then driven around the lake fast enough so that the dissolved chemicals emptied into the lake by the venturi effect. A piece of wire screening in front of the drain hole prevented large pieces of undissolved sodium nitrate from being washed out. The process was repeated 3 to 6 times taking 30-90 minutes depending on water temperature (Schindler et al. 1971).

"Barrel Method"

Chemicals were added to the lake using a point-source gravity-feed method. A 202 L polyethylene barrel was positioned close to the shoreline (Fig. 1). Chemicals were added to the barrel and dissolved in water from the lake. A piece of screening was placed around the inside of the barrel bottom to prevent any large pieces of fertilizer from plugging the line. Originally, in 1975 the nutrient solution was siphoned out of the barrel (Shearer, personal communication). However siphoning was replaced later in 1975 by the following method. The barrel had a drain near the bottom to which tygon tubing was attached. The nutrient solution then drained into the lake by gravity flow through tubing extending from the bottom of the barrel into the lake at a depth of 15-60 cm. Flow was regulated by a clamp. The nutrient solution was distributed over the lake by lake water movements. Flow was regulated so that it took about 3 days to empty the barrel. Nutrient additions were usually made on a weekly basis subsequent to water chemistry sampling.

"Raft method"

This method was designed to inject nutrients into the hypolimnion of L302N. Additions were made using a 202 L barrel mounted on a raft anchored near the deepest point of the north basin. Fertilizer was placed in a fine-screened hopper in the barrel and dissolved in water pumped from a depth of 8 m, which was well below the thermocline (Fig. 2). The outlet of the barrel, which drained the nutrients back to the hypolimnion, was located 1 m below the inlet and on the opposite side of the raft. Screens in the barrel kept undissolved fertilizer from being washed into the hypolimnion (Schindler et al. 1980).

"Prop-wash mix method"

Acid was added by slowly pouring concentrated H_2SO_4 over the rear of a moving boat, into the prop-wash of a 15 hp outboard motor running at full throttle. The lake was criss-crossed several times during the acid addition. Physical mixing studies of lakes in the area (Quay et al. 1978) indicated that the acid should have been homogeneously mixed in the epilimnion within a few hours of addition (Schindler et al. 1980).

"Prop-tube mix method"

A rack constructed of wood was placed on the gunwales of a fiberglass boat so that the compartments for holding the acid carboys are overhanging the sides of the boat (Fig. 3a-b). A piece of 3/4" tygon tubing was inserted into a 11/16" hole drilled into a carboy cap. The cap-tube assembly was screwed on the carboy and the carboy was then inverted in the rack compartment. The tube length was determined by the distance from the rack to the position in the prop wash where maximum mixing occurs (Fig. 3c). The boat was driven around the lake at full speed criss-crossing the lake several times. A variation of cap tube assembly was used in the nitric acid drum screw-cap. However an air-bleed line was also necessary because of the air-tight seal.

SOURCES OF NUTRIENT AND ACIDS

All bulk chemicals were obtained from two Winnipeg firms (C-I-L Ltd. and Harrisons & Crossfield Ltd.). Prices quoted are in 1983 dollars.

The sulfuric acid (H_2SO_4) used in acidification manipulations of L114 (Table 1), L223 (Table 2) and 302S (Table 9) is a 36N electrolytic grade acid with a specific gravity of 1.835 $g{\cdot}L^{-1}$. It is available in 18.9 L plastic cubitainers and costs $0.40 $\cdot kg^{-1}$ or $13.60 a carboy. The acid was moved to 302S via snowmobile and to L223 by helicopter. The acid cubitainers were stored off the ground under tarps. There seems to be no effect on the acid in regard to storage time or freezing. Exposure of the acid to ultra-violet light causes the acid to darken in colour. This is caused by u.v. light breaking down the plastic container and releasing organics into the acid. There is no effect on the acid strength by this process. Our analysis shows that this grade of sulfuric acid contains insignificant amounts of heavy metals in the quantities added to the lake (Table 12). Using the Al analysis from Batch C as a worst case example we contribute only 12.2 grams of Al to L223 per year. This is 0.13 $\mu g{\cdot}L^{-1}$ of Al added to the epilimnion which is an insignificant amount. The mean epilimnion value of Al in L223 is 40.8 $\mu g{\cdot}L^{-1}$ in 1982. The variance in batches is probably due to contamination at the factory or by our handling methods. In any case, the different batches do not affect heavy metal concentrations in any of the acidified lakes.

The nitric acid (HNO_3) used in L302N is a 16N 40° Be technical grade acid. Its assay (HNO_3) is guaranteed to be not less than 61.38% and to have a mean of 62.84%. It is available in 49.2 L stainless steel drums each weighing 77 kg and has a specific mean gravity of 1.51 $g{\cdot}L^{-1}$. The drum has a $250.00 deposit with the acid costing $0.61 $\cdot kg^{-1}$ or $47.00 $\cdot drum^{-1}$.

The nitric acid also had insignificant amounts of heavy metals (Table 12) in the quantities added to the lake.

Nutrients used in fertilization experiments were either flown in by helicopter or moved in by snowmobile. They were stored off the ground under tarps with only enough for each year being ordered at a time. The sucrose was stored in large culverts with steel bars at the ends to prevent bears from eating the sucrose.

The nitrogen source used in L226NE (Table 3), L226SW (Table 4), L227 (Table 5), L230 (Table 6), L303 (Table 10) and L304 (Table 11, 1975-1976) was sodium nitrate ($NaNO_3$). This was a commercially available fertilizer that comes in 25 or 45 kg bags, and costs $0.54 $\cdot kg^{-1}$. The nitrogen source used in L302N (Table 8) and L304 (Table 11 1971-1974) was ammonium chloride (NH_4Cl).

The phosphorus source used in lakes 227, 230, 261 (Table 7), 302N, 303 and 304 was phosphoric acid (H_3PO_4). We used a 85% food grade that came in 22.7 L (32 kg) cubitainers and cost $2.00 $\cdot kg^{-1}$. The phosphoric acid was stored year round in a heated area to prevent it from freezing, and transported as necessary to the various lakes.

The carbon source used in lakes 226NE, 226SW, 302N and 304 was sucrose ($C_{12}H_{22}O_{11}$). The brand used was Manitoba Sugar and it came in 11 kg bags.

SAFETY MEASURES AND PROBLEMS

All the acids used were extremely corrosive and the following safety procedures were followed for each addition. Additions were carried out by one or two persons depending on the quantities added. Two persons were required for the nitric acid additions because of the weight and awkwardness of the drum design. Each person wore acid resistant neoprene jackets, pants, gauntlets and boots. In addition a clear acid resistant face shield was worn at all times. A tube of sodium bicarbonate ($NaHCO_3$) solution was prepared before any acid is handled. This was so the person can neutralize any spills immediately. This $NaHCO_3$ solution was also carried in the boat as the acid was being added. When additions were completed, acid carboys, acid suits and the boat were rinsed out with the bicarbonate solution. The solution used in the neutralization was poured back in the tub and deposited on the shore so that very little bicarbonate solution reached the lake.

There were some problems to watch for. The sulfuric acid carboys were enclosed in cardboard cartons that tended to break up from acid leakage, rain, etc. This created a disposal problem because of the remoteness of the lake. We obtained a fire permit and burned our boxes in a 45 gallon gas drum under controlled conditions. Persons who handled the acid had to be cautious due to occasional carboys splitting open. The tygon tubing sometimes falls out of the cup or gets caught in the prop so a spare was kept in the boat.

During 1982 and 1983 our nitric acid drums were stored at the previous experiment's fertilizer site. The ground cover was composed of organic matter such as needles, peat and humus. One drum stored on its side leaked with the result being a small fire. Fortunately, this was discovered before much damage occurred. The acid dump is now located on a bare rock point.

The nitric acid gives off some toxic fumes so a respirator mask was required when large quantities were being added. Each drum weighs 77 kg when full and therefore provided balancing problems in the boat. This can be avoided if a wide boat is employed.

In order to ensure that a lake is kept at its target pH, four to five daily measurements are required per week. This is especially true in spring and fall when large quantities of acid are required to keep the lake near its target pH. At ELA, our pH samples are taken using a volunteer system, coordinated by the field technician, involving any project member visiting that lake during a day.

ACKNOWLEDGMENTS

I would like to thank Michael Turner and Thérese Ruszczynski for their contributions in gathering the lake addition data. I would like to thank the reviewers especially Michael Turner for his helpful suggestions. A special thank you to Lillian Wilson who typed this report.

REFERENCES

FEE, E.J. 1979. A relation between lake morphometry and primary production and its use in interpreting whole-lake eutrophication experiments. Limnol. Oceanogr. 24(3): 401-416.

QUAY, P.D., R.H. HESSLEIN, W.S. BROECKER, and D.W. SCHINDLER. 1978. Measurements of vertical and horizontal diffusion in experimental lakes and enclosures using injections of tritiated water. Can. Fish. Mar. Serv. Data Rep. 43: 39 p.

SCHINDLER, D.W. 1977. Evolution of phosphorus limitation in lakes. Science (Wash. DC) 195: 260-262.

SCHINDLER, D.W., F.A.J. ARMSTRONG, S.K. HOLMGREN, and G.J. BRUNSKILL. 1971. Eutrophication of Lake 227, Experimental Lakes Area, northwestern Ontario, by addition of phosphate and nitrate. J. Fish. Res. Board Can. 28(11): 1763-1782.

SCHINDLER, D.W., and M.A. TURNER. 1982. Biological, chemical and physical responses of lakes to experimental acidification. Water Air Soil Pollut. 18: 259-271.

SCHINDLER, D.W., T. RUSZCZYNSKI, and E.J. FEE. 1980. Hypolimnion injection of nutrient effluents as a method for reducing eutrophication. Can. J. Fish. Aquat. Sci. 37(3): 320-327.

SCHINDLER, D.W., R. WAGEMANN, R.B. COOK, T. RUSZCZYNSKI, and J. PROKOPOWICH. 1980. Experimental acidification of Lake 223, Experimental Lakes Area: I. Background data and the first three years of acidification. Can. J. Fish. Aquat. Sci. 37(3): 342-354.

Table 1. L114 acid additions[1].

Year	Date	Sulfuric acid: Litres added	Sulfuric acid: Kg H_2SO_4 added	Time-weighted Mean Epilimnion pH	Method of addition
1979	Jul 23 - Oct 15 (4 additions)[2]	134.4	242	5.82	Prop-tube
1980	May 13 - Sep 29 (7 additions)	235.2	423.5	6.11	Prop-tube
1981	May 11 - Sep 28 (6 additions)	201.6	363	6.05	Prop-tube
1982	May 17 - Oct 4 (6 additions)	201.6	363	5.90	Prop-tube
1983	May 23 - Oct 10 (6 additions)	201.6	363	5.94	Prop-tube
	Total	974.4	1 754.5		

[1] details of additions in Appendix 1
[2] each addition was 33.6 L H_2SO_4
N.B. Method for pH determination was changed in July, 1980, therefore values prior to 1981 may be a little lower than those reported here.

Table 2. L223 acid additions[1].

Year	Date	Sulfuric acid: Litres added	Sulfuric acid: Kg H_2SO_4 added	Time-weighted Mean Epilimnion pH	Method of addition
1976		5 537.8	9 968	6.49	Prop-wash mix
1977	May 4 - Oct 17 (17 additions)	2 910.6	5 239	6.13	Prop-wash mix
1978	May 8 - Oct 23 (6 additions)	3 777.4	6 799	5.93	Prop-wash mix
1979	May 21 - Oct 29 (45 additions)	2 816.1	5 069	5.64	Prop-tube mix
1980	May 5 - Oct 20 (33 additions)	3 099.6	5 576	5.59	Prop-tube mix
1981	May 6 - Oct 22 (35 additions)	3 553.2	6 392	5.02	Prop-tube mix
1982	May 5 - Oct 26 (38 additions)	3 458.7	6 222	5.09	Prop-tube mix
1983	May 10 - Oct 28 (30 additions)	2 230.2	4 014	5.13	Prop-tube mix
	Total	27 383.6	49 290		

[1] details of additions in Appendix 2.
N.B. Method for pH determination was changed in July, 1980, therefore values prior to 1981 may be a little lower than those reported here.

Table 3. L226NE fertilizer additions.

		Sodium nitrate				Sucrose				Phosphoric acid					
Year	Date	$Kg \cdot wk^{-1}$	Total kg	$Kg\ N \cdot wk^{-1}$	Total Kg N	$Kg \cdot wk^{-1}$	Total Kg	$Kg\ C \cdot wk^{-1}$	Total Kg C	$L \cdot wk^{-1}$	Total L	$Kg \cdot wk^{-1}$	$Kg\ P \cdot wk^{-1}$	Total Kg P	Method of addition
1973	May 21 - Oct 2 (20 additions in 21 wk)	45.4	953.4	7.5	157.3	34.0	714	14.3	299.9	3.1	65.1	5.3	1.4	29.4	Boat
1974	May 21 - Oct 9 (21 additions)	45.4	953.4	7.5	157.3	34.0	714	14.3	299.9	3.1	65.1	5.3	1.4	29.4	Boat
1975	May 12 - Sep 24 (20 additions)	45.4	908	7.5	150.0	34.0	680	14.3	286.3	3.1	62	5.3	1.4	28.0	Boat/barrel
1976	May 24 - Oct 4 (20 additions)	45.4	908	7.5	150.0	34.0	680	14.3	286.3	3.1	62	5.3	1.4	28.0	Barrel
1977	May 25 - Oct 5 (20 additions)	45.4	908	7.5	150.0	34.0	680	14.3	286.3	3.1	62	5.3	1.4	28.0	Barrel
1978	May 17 - Sep 27 (20 additions)	45.4	908	7.5	150.0	34.0	680	14.3	286.3	3.1	62	5.3	1.4	28.0	Barrel
1979	May 30 - Oct 10 (20 additions)	45.4	908	7.5	150.0	34.0	680	14.3	286.3	3.1	62	5.3	1.4	28.0	Barrel
1980	May 7 - Sep 16 (20 additions)	45.4	908	7.5	150.0	35.0	700	14.7	294	3.1	62	5.3	1.4	28.0	Barrel
Total additions 1973-1980			7 354.8		1 214.6		5 528		2 325.3		502.2			226.8	

Table 4. L226SW fertilizer additions.

Year	Date	Sodium nitrate $NaNO_3$				Sucrose C				Method of addition
		$Kg \cdot wk^{-1}$	Total kg	$Kg\ N \cdot wk^{-1}$	Total Kg N	$Kg \cdot wk^{-1}$	Total Kg	$Kg\ C \cdot wk^{-1}$	Total Kg C	
1973	May 21 - Oct 2 (20 additions)	45.4	953.4	7.5	157.3	34.0	714	14.3	299.9	Boat
1974	May 21 - Oct 9 (21 additions)	45.4	953.4	7.5	157.3	34.0	714	14.3	299.9	Boat and barrel
1975	May 12 - Sep 24 (20 additions)	45.4	908	7.5	150.0	34.0	680	14.3	286.3	Barrel
1976	May 24 - Oct 4 (20 additions)	45.4	908	7.5	150.0	34.0	680	14.3	286.3	Barrel
1977	May 25 - Oct 5 (20 additions)	45.4	908	7.5	150.0	34.0	680	14.3	286.3	Barrel
1978	May 17 - Sep 27 (20 additions)	45.4	908	7.5	150.0	34.0	680	14.3	286.3	Barrel
1979	May 30 - Oct 10 (20 additions)	45.4	908	7.5	150.0	34.0	680	14.3	286.3	Barrel
1980	May 7 - Sep 16 (20 additions)	45.4	908	7.5	150.0	35.0	700	14.7	294	Barrel
Total additions 1973-1980			7 354.8		1 214.6		5 528		2 325.3	

Table 5. L227 Fertilizer additions.

Year	Date	Sodium nitrate $NaNO_3$				Phosphoric acid H_3PO_4						Method of Addition
		Kg•wk^{-1}	Total kg	Kg N•wk^{-1}	Total Kg N	L•wk^{-1}	Total L	Kg•wk^{-1}	Total Kg	Kg P•wk^{-1}	Total Kg P	
1969[1]	Jun 26 - Oct 16 (17 weekly additions)	90.7	1 542.2	15.0	254.5				77.1	1.18	20.0	Boat
1970	May 26 - Oct 13 (21 weekly additions)	90.7	1 905	15.0	315	2.5	52.5	4.25	89.25	1.14	24.0	Boat
1971	May 18 - Oct 5 (21 weekly additions)	90.7	1 905	15.0	315	2.5	52.5	4.25	89.25	1.14	24.0	Boat
1972	May 16 - Oct 3 (21 weekly additions)	90.7	1 905	15.0	315	2.5	52.5	4.25	89.25	1.14	24.0	Boat
1973	May 22 - Oct 8 (21 weekly additions)	90.7	1 905	15.0	315	2.5	52.5	4.25	89.25	1.14	24.0	Boat
1974	May 21 - Oct 9 (21 weekly additions)	90.7	1 905	15.0	315	2.5	52.5	4.25	89.25	1.14	24.0	Boat
1975	May 13 - Sep 25 (20 weekly additions)	34.0	680.4	5.61	112.2	2.5	50.0	4.25	85.0	1.14	22.8	Barrel
1976	May 25 - Oct 5 (20 weekly additions)	34.0	680.4	5.61	112.2	2.5	50.0	4.25	85.0	1.14	22.8	Barrel
1977	May 26 - Oct 6 (20 weekly additions)	34.0	680.4	5.61	112.2	2.5	50.0	4.25	85.0	1.14	22.8	Barrel
1978	May 9 - Sep 19 (20 weekly additions)	34.0	680.4	5.61	112.2	2.5	50.0	4.25	85.0	1.14	22.8	Barrel
1979	May 29 - Oct 9 (20 weekly additions)	34.0	680.4	5.61	112.2	2.5	50.0	4.25	85.0	1.14	22.8	Barrel
1980	May 6 - Sep 16 (20 weekly additions)	34.0	680.4	5.61	112.2	2.5	50.0	4.25	85.0	1.14	22.8	Barrel
1981	May 4 - Sep 15 (20 weekly additions)	34.0	680.4	5.61	112.2	2.5	50.0	4.25	85.0	1.14	22.8	Barrel
1982	May 11 - Sep 21 (20 weekly additions)	34.0	680.4	5.61	112.2	2.5	50.0	4.25	85.0	1.14	22.8	Barrel
1983	May 11 - Sept 20 (20 weekly additions)	34.0	680.4	5.61	112.2	2.5	50.0	4.25	85.0	1.14	22.8	Barrel
Total additions 1969-1983			17 198.8		2 610.3		712.5				325.2	

[1] 1969 phosphorus source was $NaHPO_4$

Table 6. L230 fertilizer additions.

Year	Date	Sodium nitrate Kg $NaNO_3$	Kg N	Phosphoric acid L H_3PO_4	Kg P	Method of Addition
1974	December (single addition)	544	89.6	18 L	8.23	Under ice*
1975	November 4 (single addition)	726	119.8	18 L	8.23	Under ice
	Total additions	1 270	209.6	36 L	16.46	

*nutrients were mixed in barrel on the ice then distributed under the ice by a pump

Table 7. L261 fertilizer additions.

Year	Date	Phosphoric acid L·wk^{-1}	Total L	$Kg \cdot wk^{-1}$	Total Kg	Kg P·wk^{-1}	Total Kg P	Method of Addition
1973	May 22 - Oct 8 (21 additions)	1.5	31.5	2.55	53.55	0.69	14.4	Boat
1974	May 15 - Oct 2 (21 additions)	1.5	31.5	2.55	53.55	0.69	14.4	Boat
1975	May 21 - Oct 1 (20 additions)	1.5	30.0	2.55	51.0	0.69	13.8	Barrel
1976	May 19 - Oct 6 (20 additions)	1.5	30.0	2.55	51.0	0.69	13.8	Barrel

Table 8. L302N fertilizer and acid additions.

Year	Date	Ammonium chloride Kg·wk^{-1}	Total Kg	Kg N·wk^{-1}	Total Kg N	Sucrose Kg·wk^{-1}	Total Kg	Kg C·wk^{-1}	Total Kg C	Phosphoric acid L·wk^{-1}	Total L	Kg·wk^{-1}	Total Kg	Kg P·wk^{-1}	Total Kg P	Nitric acid L added	Kg HNO_3	Time-weighted Mean epilimnion pH	Method of addition
1972*	Jun 8 - Sep 14 (15 weekly additions)	68.0	1 020.6	17.8	267.2	56.7	850.5	23.8	357.2	7.5	112.5	12.75	191.3	3.43	51.4				Raft
1973*	May 21 - Sep 24 (19 weekly additions)	68.0	1 292	17.8	338.5	56.7	1 077	23.8	452.2	7.5	142.5	12.75	242.3	3.43	65.2				Raft
1974°	Jun 25 - Sep 18 (15 weekly additions)	90.7	1 361	23.8	356.5	71.8	1 077	30.2	452.2	10.0	150	17.0	255	4.57	68.6				Raft
1975	May 28 -Sep 3 (15 weekly additions)	90.7	1 361	23.8	356.5	80	1 200	33.6	504	10.0	150	17.0	255	4.57	68.6				Raft
1976	May 26 - Sep 1 (15 weekly additions)	90.7	1 361	23.8	356.5	80	1 200	33.6	504	10.0	150	17.0	255	4.57	68.6				Raft
1978	May 16 - Aug 23 (15 weekly additions)	90.7	1 361	23.8	356.5	80	1 200	33.6	504	10.0	150	17.0	255	4.57	68.6				Raft
1981	(no additions)																		
1982	Jun 29 - Oct 5 (14 weekly additions)															2 282.9	3 424.4	6.71	Prop-tube
1983	May 23 - Oct 24 (26 weekly additions)															2 463.3	3 690.5	6.34	Prop-tube
Total additions			7 756.6		2 031.7		6 604.5		2 773.6		855		1 453.6		391	4 746.2	7 114.9		

*no curtain
°curtain in July

Table 9. L302S acid additions.

Year	Date	Sulfuric acid Litres added	Sulfuric acid Kg H_2SO_4 added	Time-weighted Epilimnion pH	Method of addition
1981	(no additions)			6.75	
1982	Jun 29 - Oct 5 (14 additions)	1 228.5	2 211.3	6.25	Prop-tube
1983	May 23 - Oct 24 (26 additions)	1 107.7	1 993.9	5.86	Prop-tube

Table 10. L303 fertilizer additions.

Year	Date	Phosphoric acid H_3PO_4						Sodium nitrate $NaNO_3$				Method of addition
		$L \cdot wk^{-1}$	Total L H_3PO_4	Kg $H_3PO_4 \cdot wk^{-1}$	Total Kg H_3PO_4	Kg $P \cdot wk^{-1}$	Total Kg P	$Kg \cdot wk^{-1}$	Total Kg $NaNO_3$	Kg $N \cdot wk^{-1}$	Total Kg N	
1975	May 14 - Sep 24 (20 weekly additions)	2.2	44	3.74	74.8	1.01	20.1	90.7	1 814	15.0	300	Barrel
1976	May 19 - Oct 6 (20 weekly additions)	2.2	44	3.74	74.8	1.01	20.1	90.7	1 814	15.0	300	Barrel
Total	additions 1975-1976		88		149.6		40.2		3 628		600	

Table 11. L304 fertilizer additions.

Year	Date	Ammonium chloride				Sucrose				Phosphoric acid						Sodium nitrate				Method of addition
		$Kg \cdot wk^{-1}$	Total Kg	Kg $N \cdot wk^{-1}$	Total Kg N	$Kg \cdot wk^{-1}$	Total Kg	Kg C wk^{-1}	Total Kg C	$L \cdot wk^{-1}$	Total L	$Kg \cdot wk^{-1}$	Total Kg	Kg $P \cdot wk^{-1}$	Total Kg P	$Kg \cdot wk^{-1}$	Total Kg	Kg $N \cdot wk$	Total Kg N	
1971	May 26 - Oct 13 (21 weekly additions)	34	714	8.91	187.1	22.7	476	9.53	200.1	1.5	31.5	2.17	45.5	0.685	14.4					Boat
1972	May 24 - Oct 4 (20 weekly additions)	34	680	8.91	178.2	22.7	454	9.53	190.5	1.5	30	2.17	43.4	0.685	13.7					Boat
1973	May 16 - Oct 3 (21 weekly additions)	34	714	8.91	187.1	22.7	476	9.53	200.1											Boat
1974	May 15 - Oct 2 (21 weekly additions)	34	714	8.91	178.2	22.7	476	9.53	200.1											Boat
1975	May 14 - Sep 24 (20 weekly additions)									4.0	80	6.8	136	1.83	36.6	158.8	3 175	26.2	52.4	Barrel
1976	May 19 - Oct 6 (20 weekly additions)									4.0	80	6.8	136	1.83	36.6	158.8	3 175	26.2	52.4	Barrel
Total additions 1971-1976			2 822		739.5		1 882		790.8		221.5		360.9		101.3		6 350		104.8	

Table 12. Heavy metals analysis of added acids.

Parameters analysed	HNO_3* 1981 $\mu g \cdot L^{-1}$	HNO_3 1982[A] $\mu g \cdot L^{-1}$	HNO_3 1982[B] $\mu g \cdot L^{-1}$	H_2SO_4 L302S $\mu g \cdot L^{-1}$	H_2SO_4 L223[C] $\mu g \cdot L^{-1}$	H_2SO_4 L223[D] $\mu g \cdot L^{-1}$
Fe	2 990	11 500	6 250	26 700	28 300	26 700
Mn	40	148	100	217	321	233
Cu	2 870	41	29	110	90	75
Hg		3.2	6.2	0.2	0.2	0.6
Zn	540	11	86	150	32	200
Al	370	16	87	1 490	34 400	6 910
Pb	590					
Cr	370					

A-B samples from 2 different batch numbers
C-D samples from 2 different batch numbers
*sample analysed by F.W.I. heavy metals lab prior to purchase

Table 13. Physical characteristics of manipulated ELA lakes.

Lake	Surface area (ha)	Volume $10^5 m^3$	Mean depth (m)	Maximum depth (m)
114	12.10	2.07	1.7	5.0
223	27.27	19.51	7.1	14.4
226NE	8.33	4.72	5.7	14.7
226SW	7.77	4.89	6.3	11.6
227	5.00	2.21	4.4	10.0
230	1.67	1.04	5.9	13.6
261	5.57	1.60	2.9	9.6
302N	12.80	7.32	5.7	13.8
302S	10.90	5.54	5.0	10.6
303	9.93	1.50	1.5	2.5
304	3.62	1.15	3.3	6.7

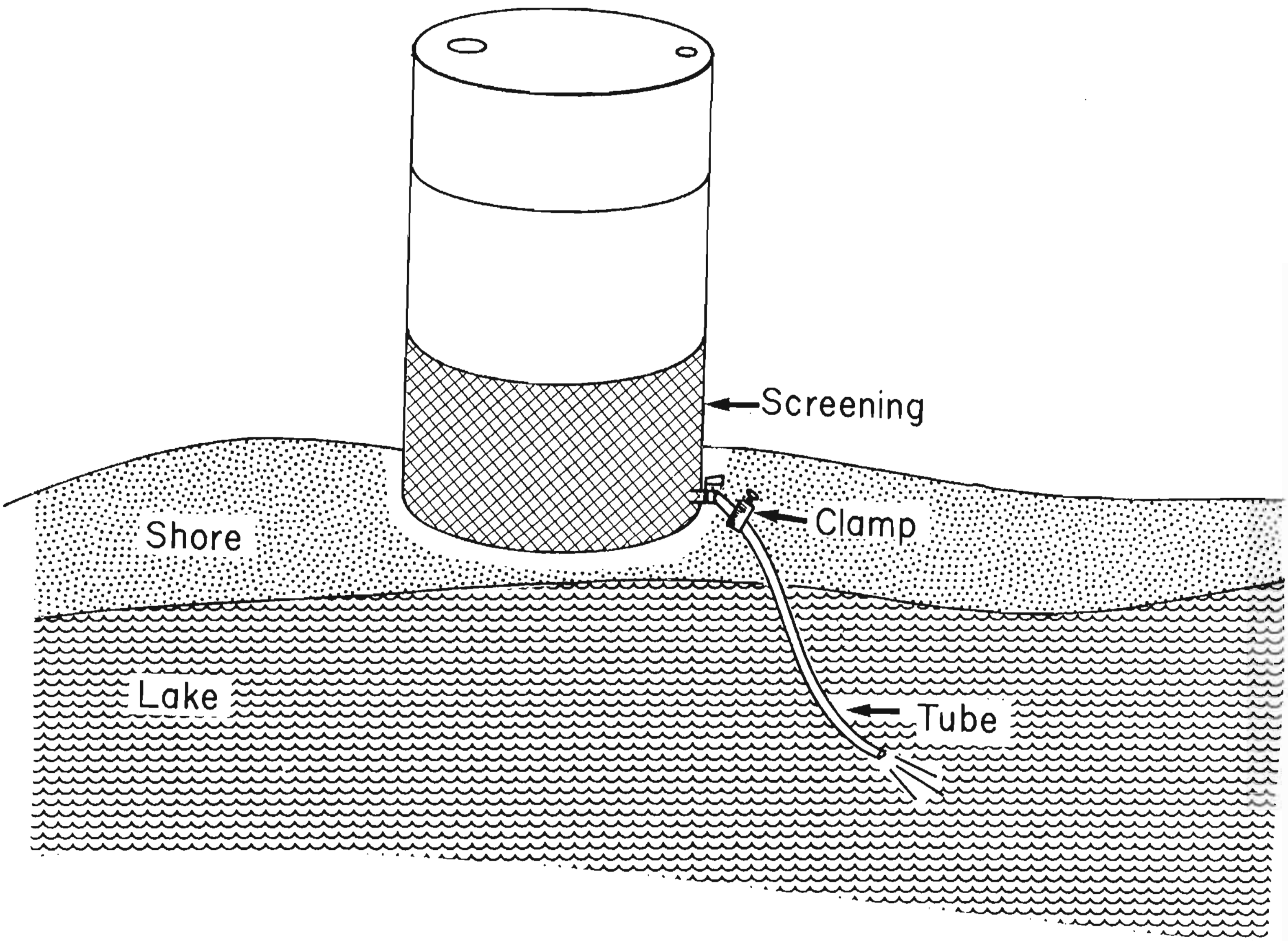

Fig. 1. "Barrel method"

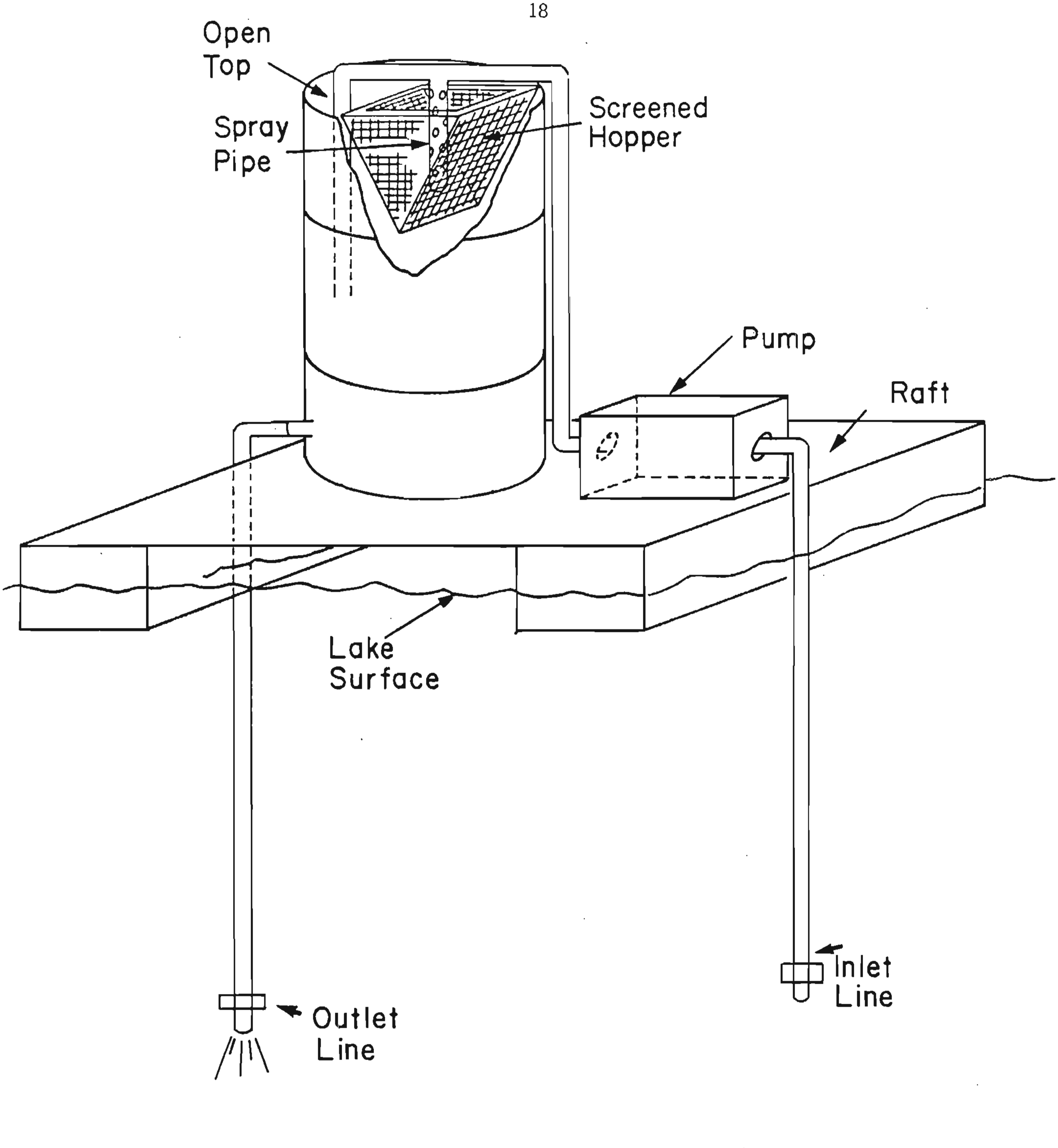

Fig. 2. "Raft method"

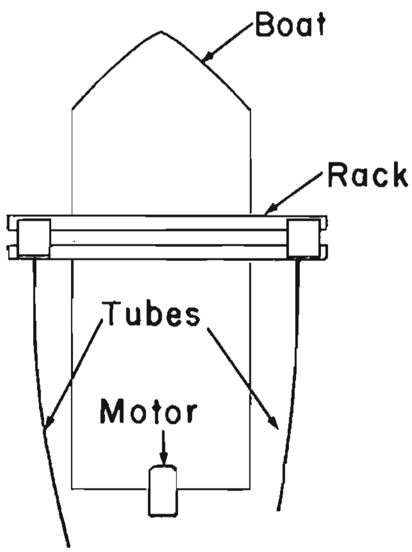

Fig. 3A

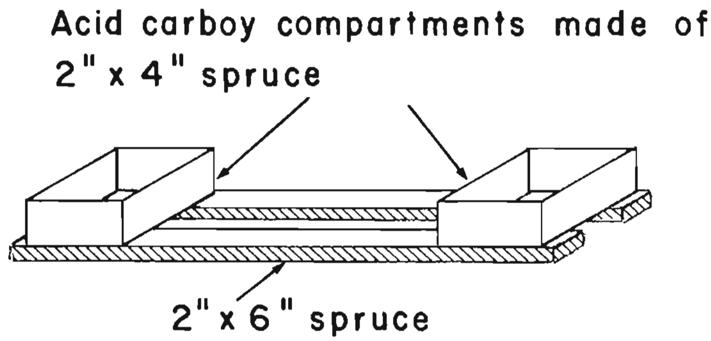

Fig. 3B

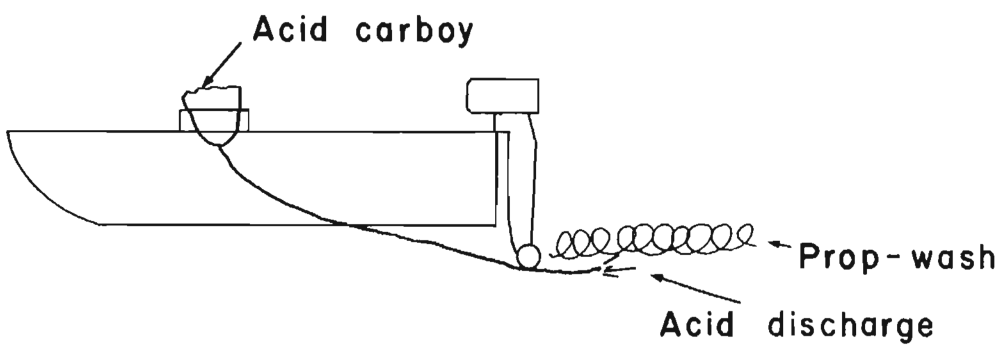

Fig. 3C

Fig. 3. "Prop-tube method"

Appendix 1. Lake 223 daily acid addition.

Year	Date	H_2SO_4 (L)	H_2SO_4 (kg)	Year	Date	H_2SO_4 (L)	H_2SO_4 (kg)
1977	May 4	283.5	408	1979	Jul 8	37.8	68
	May 9	226.8	408	cont.	Jul 12	37.8	68
	May 23	226.8	408		Jul 16	37.8	68
	Jun 6	113.4	204		Jul 18	37.8	68
	Jun 13	226.8	408		Jul 23	37.8	68
	Jun 20	226.8	408		Jul 30	37.8	68
	Jul 20	134.4	204		Jul 31	18.9	34
	Jul 26	113.4	204		Aug 1	56.7	102
	Aug 2	113.4	68		Aug 6	37.8	68
	Aug 9	113.4	204		Aug 9	56.7	102
	Aug 17	113.4	204		Aug 10	37.8	68
	Aug 23	151.2	272		Aug 13	183.4	204
	Aug 29	151.2	272		Aug 16	37.8	68
	Sep 6	226.8	408		Aug 22	37.8	68
	Sep 14	226.8	408		Aug 27	56.7	102
	Sep 17	113.4	204		Sep 3	56.7	102
					Sep 6	37.8	68
1978	May 8	113.4	204		Sep 10	56.7	102
	May 15	113.4	204		Sep 11	56.7	102
	May 22	113.4	204		Sep 17	56.7	102
	May 29	113.4	204		Sep 18	56.7	102
	Jun 5	113.4	204		Sep 24	75.6	136
	Jun 12	113.4	204		Sep 26	37.8	68
	Jun 19	226.8	408		Oct 1	94.5	170
	Jun 26	226.8	408		Oct 3	94.5	170
	Jul 10	113.4	204		Oct 8	37.8	68
	Jul 17	113.4	204				
	Jul 31	117.2	210.8	1980	May 5	132.3	238
	Aug 2	104.0	187		May 6	94.5	170
	Aug 7	151.2	272		May 7	75.6	136
	Aug 8	75.6	136		May 8	37.8	68
	Aug 14	56.7	102		May 12	151.2	272
	Aug 21	37.8	68		May 13	75.6	136
	Aug 28	37.8	68		May 14	75.6	136
	Sep 4	56.7	102		May 19	56.7	102
	Sep 8	37.8	68		May 20	56.7	102
	Sep 11	183.4	204		May 23	37.8	68
	Sep 15	56.7	102		Jun 2	113.4	204
	Sep 18	56.7	102		Jun 11	56.7	102
	Sep 21	183.4	204		Jun 12	37.8	68
	Sep 25	56.7	102		Jun 19	75.6	136
	Sep 29	183.4	204		Jul 1	75.6	136
	Oct 5	56.7	102		Jul 2	94.5	170
	Oct 9	183.4	204		Jul 10	75.6	136
	Oct 12	56.7	102		Jul 15	94.5	170
	Oct 16	151.2	272		Jul 25	94.5	170
	Oct 19	264.6	476		Jul 29	56.7	102
	Oct 23	189.0	340		Aug 12	18.9	34
					Aug 21	56.7	102
1979	May 18	183.4	204		Aug 28	37.8	68
	May 23	264.6	476		Sep 3	94.5	170
	May 28	226.8	408		Sep 5	56.7	102
	Jun 4	567	102		Sep 8	75.6	136
	Jun 8	75.6	136		Sep 11	75.6	136
	Jun 12	56.7	102		Sep 15	151.2	272
	Jun 15	37.8	68		Sep 18	189.0	340
	Jun 18	37.8	68		Sep 22	189.0	340
	Jun 21	18.9	34		Sep 24	189.0	340
	Jun 25	37.8	68		Sep 29	378.0	680
	Jun 27	37.8	68		Oct 20	75.6	136
	Jul 3	56.7	102				
	Jul 5	37.8	68				

Appendix 1. Lake 223 daily acid addition - continued

Year	Date	H_2SO_4 (L)	H_2SO_4 (kg)
1981	May 6	245.7	442
	May 8	245.7	442
	May 11	283.5	510
	May 12	378.0	680
	May 25	75.6	136
	Jun 1	56.7	102
	Jun 9	37.8	68
	Jun 15	37.8	68
	Jun 17	56.7	102
	Jun 19	94.5	170
	Jun 22	94.5	170
	Jul 9	75.6	136
	Jul 12	75.6	136
	Jul 27	75.6	136
	Aug 10	37.8	68
	Aug 13	37.8	68
	Aug 18	56.7	103
	Aug 19	37.8	68
	Aug 26	37.8	68
	Sep 1	37.8	68
	Sep 2	56.7	102
	Sep 7	37.8	68
	Sep 8	56.7	102
	Sep 14	56.7	102
	Sep 16	56.7	102
	Sep 21	113.4	204
	Sep 24	113.4	204
	Sep 28	189.0	340
	Oct 1	283.5	510
	Oct 5	113.4	204
	Oct 9	113.4	204
	Oct 19	75.6	136
	Oct 22	75.6	136
1982	May 5	226.8	408
	May 6	226.8	408
	May 7	151.2	272
	May 10	75.6	136
	May 26	75.6	136
	May 28	113.4	204
	Jun 18	56.7	102
	Jun 21	56.7	102
	Jun 28	56.7	102
	Jul 5	94.5	170
	Jul 13	94.5	170
	Jul 19	94.5	170
	Jul 23	75.6	170
	Jul 27	75.6	136
	Jul 29	56.7	136
	Aug 2	37.8	68
	Aug 9	56.7	102
	Aug 11	75.6	136
1982 cont.	Aug 13	56.7	102
	Aug 16	37.8	68
	Aug 20	37.8	68
	Aug 23	94.5	170
	Aug 27	56.7	102
	Aug 30	37.8	68
	Sep 6	75.6	136
	Sep 9	113.4	204
	Sep 20	113.4	204
	Sep 27	75.6	136
	Sep 30	189.0	340
	Oct 4	113.4	204
	Oct 6	283.5	510
	Oct 11	37.8	68
	Oct 18	56.7	102
	Oct 21	75.6	136
	Oct 26	56.7	102
1983	May 10	226.8	408
	May 12	37.8	68
	May 16	56.7	102
	May 23	56.7	102
	May 27	94.5	170
	May 30	75.6	136
	Jun 1	94.5	170
	Jun 6	75.6	136
	Jun 13	75.6	136
	Jun 16	37.8	68
	Jun 19	56.7	102
	Jun 27	37.8	68
	Jul 7	37.8	68
	Jul 11	37.8	68
	Jul 19	37.8	68
	Aug 9	37.8	68
	Aug 29	18.9	34
	Sep 5	56.7	102
	Sep 12	75.6	136
	Sep 15	283.5	510
	Sep 19	75.6	136
	Sep 26	37.8	68
	Oct 3	113.4	204
	Oct 5	113.4	204
	Oct 10	113.4	204
	Oct 12	113.4	204
	Oct 18	56.7	102
	Oct 20	113.4	204
	Oct 24	94.5	170
	Oct 28	113.4	204

Appendix 2. L302N acid additions.

Year	Date	HNO_3 (L)	HNO_3 (kg)	Year	Date	HNO_3 (L)	HNO_3 (kg)
1982	Jun 29	477.0	715.5	1983	May 23	49.2	73.8
	Jul 6	196.8	295.2		May 26	49.2	73.8
	Jul 13	98.4	49.2		May 31	49.2	73.8
	Jul 20	69.0	103.5		Jun 2	49.2	73.8
	Jul 27	71.5	107.3		Jun 8	49.2	73.8
	Aug 3	36.2	54.3		Jun 14	196.8	295.2
	Aug 10	196.8	295.2		Jun 28	49.2	73.8
	Aug 17	74.0	111		Jun 30	49.2	73.8
	Aug 24	79.1	118.7		Jul 5	147.6	221.4
	Aug 31	393.6	589.5		Jul 7	147.6	221.4
	Sep 8	246.0	369		Aug 3	49.2	73.8
	Sep 22	147.6	221.4		Aug 5	49.2	73.8
	Sep 28	147.6	221.4		Aug 9	98.4	147.6
	Oct 5	49.2	73.8		Aug 16	98.4	147.6
					Aug 23	98.4	147.66
					Aug 25	98.4	147.6
					Aug 30	147.6	221.4
					Sep 1	147.6	221.4
					Sep 6	49.2	73.8
					Sep 13	98.4	147.6
					Sep 15	98.4	147.6
					Sep 21	98.4	147.6
					Sep 27	98.4	147.6
					Oct 4	196.8	295.2
					Oct 11	98.4	147.6
					Oct 24	98.4	147.6

Appendix 3. L302S acid additions.

Year	Date	H_2SO_4 (L)	H_2SO_4 (kg)	Year	Date	H_2SO_4 (L)	H_2SO_4 (kg)
1982	Jun 29	283.5	510	1983	May 23	26.3	47.3
	Jul 6	151.2	272		May 26	26.3	47.3
	Jul 13	75.6	136		May 31	26.9	48.4
	Jul 20	37.8	68		Jun 2	26.9	49.4
	Jul 27	37.8	68		Jun 8	26.9	48.4
	Aug 3	18.9	34		Jun 14	105.0	189.0
	Aug 10	75.6	136		Jun 28	26.9	48.4
	Aug 17	37.8	68		Jun 30	26.9	48.4
	Aug 24	37.8	68		Jul 5	78.5	141.3
	Aug 31	189.0	340		Jul 7	78.5	141.3
	Sep 8	132.3	238		Aug 3	26.9	48.4
	Sep 22	75.6	136		Aug 5	26.9	48.4
	Sep 28	56.7	102		Aug 9	37.8	68.0
	Oct 5	18.9	34		Aug 16	37.8	68.0
					Aug 23	37.8	68.0
					Aug 25	37.8	68.0
					Aug 30	75.6	136.0
					Sep 1	56.7	102.0
					Sep 6	18.9	34.0
					Sep 13	37.8	68.0
					Sep 15	37.8	68.0
					Sep 21	37.8	68.0
					Sep 27	37.8	68.0
					Oct 4	75.6	136.0
					Oct 11	37.8	68.0
					Oct 24	37.8	68.0