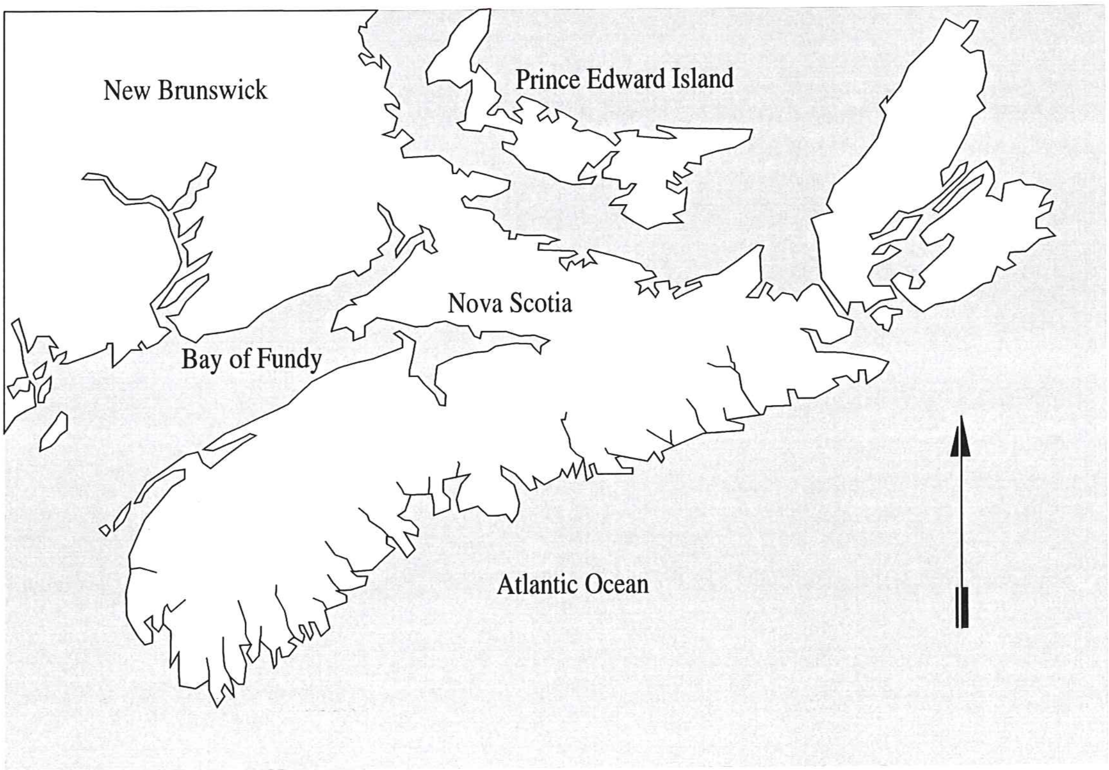
REPORT SNO 4434-2001

Recommended Liming Strategies for Salmon Rivers in Nova Scotia, Canada



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REPORT

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Abstract

The Southern Upland of Nova Scotia is acidified due the extreme sensitive ecosystems combined with being down-wind from large sulphur emission sites in southern Canada and northern US. Atlantic Salmon populations have disappeared from 14 rivers and populations have been damaged in another 35 rivers. Only rivers with pH>5.4 have non-damaged populations. Attempts to improve this situation have been restricted to the genereal emission control plans of Canada. No liming program exists at present. This report gives detailed information regarding liming strategies in general and for four major river systems in particular. East and West River, Sheet Harbour, together with La Have and Medway River are regarded as being typical representatives of the damaged rivers. Liming of these rivers is possible, and a combination of lake liming, river lime dosing and catchment liming is recommended. Suggestions are also made regarding the approach towards a relatively high-quality liming strategy for the province, and the establishment of a monitoring program for water chemistry and biology.

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Southern Upland Recovery Plan

Recommended Liming Strategies for Salmon Rivers in Nova Scotia, Canada.

Preface

The Atlantic Salmon Federation contacted NIVA in May 2000 regarding help to protect salmon populations in acidified rivers in Nova Scotia. Based on a letter from NIVA of June 6, 2000 and contact between the parties after that, a contract was signed in May 2001.

The author visited Nova Scotia in June 2001, and this report is partly based on fieldwork over a nine-day period. I would like to thank Lewis Hinks of the Federation for his hospitality and for bringing me in contact with experienced people during my stay in Nova Scotia. I would also like to thank Wesley White for providing data on lakes and catchments (see Appendix) for completion of this report.

Jarle Håvardstun and Lise Tveiten at NIVA helped with preparing pictures and maps for the report. Miljøkalk DA provided the pictures of different liming techniques.

The work was financed by Department of Fisheries and Oceans, Nova Scotia Department of Agriculture and Fisheries, the Canada/Nova Scotia Cooperation Agreement on Economic Diversification, Nova Scotia Power Corporation, Nova Scotia Salmon Association, and the Atlantic Salmon Federation.

Grimstad, December 4, 2001

Atle Hindar

Contents

1. Summary

The Southern Upland of Nova Scotia is acidified due the extreme sensitive ecosystems combined with being down-wind from large sulphur emission sites in southern Canada and northern US. Atlantic Salmon populations have disappeared from 14 rivers and populations have been damaged in another 35 rivers. Only rivers with pH>5.4 have non-damaged populations.

Attempts to improve this situation have been restricted to the genereal emission control plans of Canada. No liming program exists at present. However, a Southern Upland recovery plan is being developed by Department of Fisheries and Oceans, Nova Scotia Department of Agriculture and Fisheries, Nova Scotia Power Corporation, Nova Scotia Salmon Association and the Atlantic Salmon Federation. Part of the plan involves exploring acid rain mitigation techniques.

This report gives detailed information regarding liming strategies in general and for four major river systems in particular. Recommended liming strategies and liming techniques in this report are based on the Scandinavian experience with mitigation against acidified rivers and lakes during the last 20 years.

East and West River, Sheet Harbour, together with La Have and Medway River are regarded as being typical representatives of the damaged rivers. The rivers are characterized by being divided into several large tributaries. Large headwater lakes are few, and lakes in the middle and lower parts of the catchments have short water-retention times.

The area is characterised by dense forests in a relatively flat landscape. Overview is difficult from the ground and access to rivers and lakes is largely by the many roads that have been made for transporting logs out of the forest or for access to dams at lake outlets. Although there is access to most parts of the catchments, settlements are few in large areas.

Liming of these rivers is possible, and a combination of lake liming, river lime dosing and catchment liming is recommended. Amounts of limestone material and dosages are calculated on basis of a water quality target of pH 5.5 and available data on lakes, rivers, water chemistry and runoff. Assumptions are made on limestone quality and dissolution.

Suggestions are also made regarding the approach towards a relatively high-quality liming strategy for the province, and the establishment of a monitoring program for water chemistry and biology.

2. Background

Rivers and lakes in Nova Scotia are acidified due to anthropogenic sulphur deposition (Watt et al. 1979, 1983; Watt 1981), and this province has suffered more from acidification than any other region of North America. The combination of slowly weathering bedrock and acid deposition has deteriorated Atlantic salmon populations in 14 of 63 Nova Scotian Atlantic Upland rivers (Watt 1984; Watt et al. 2000). 20 of the rivers are severely impacted, and additional 15 rivers are lightly impacted. Only 14 of the rivers, those with pH > 5.4, are not significantly impacted by acidification. Acidification is one of several threats to Atlantic salmon populations in Canada, see overview by Watt (1989).

The potential of acidification is not surprising because Nova Scotia is downwind (northeast and east) of large sulfur-emission sources in northern parts of the U.S. and southern Canada. The bedrock of the southern upland of Nova Scotia is composed by slowly weathering minerals, as granites and metamorphic rocks, rendering the area vulnerable to acidifcation.

Rivers in Nova Scotia are also acid due to natural sources, such as wetlands dominated by Sphagnum mosses and forests. These areas produce high amounts of dissolved organic matter, which is transported to the surface waters. Typical concentrations of dissolved organic carbon of 5-30 mg L^{-1} DOC are found in the acidified rivers in the Southern Uplands (DFO 2000).

Preacidification water chemistry in this part of Nova Scotia is thus controlled by very low base-cation production due to slowly weathering bedrock, dissolved organics from forests, peat and wetlands and ions from sea-salt deposition (Gorham 1957). Although natural acids reduce pH significantly in these dilute waters, the effect of acid deposition on surface waters in Nova Scotia is clear (Gorham et al. 1986).

A Southern Upland recovery plan is being developed by Department of Fisheries and Oceans, Nova Scotia Department of Agriculture and Fisheries, Nova Scotia Power Corporation, Nova Scotia Salmon Association and the Atlantic Salmon Federation. Part of the plan involves exploring acid rain mitigation techniques.

Currently, the limited liming efforts carried out in Nova Scotia is by winter headwater lake liming. A review of the projects in Nova Scotia that conducted liming this way showed that this technique worked to produce an increase in pH levels in the target lakes. This technique relies on sufficient ice thickness to allow safe transport of lime on the ice. With changing climate and milder winters being experienced in the Southern Upland Region it is not always safe to apply lime in this way. The stream liming efforts in Nova Scotia, involving limestone gravel, do not secure good water quality at moderate and high flow. Alternate ways to mitigate for acid rain must be found. An estimate of total neutralisation needs and costs for mitigating the acidified Atlantic salmon producing rivers was made by Watt (1986).

This report presents adequate liming strategies and techinques (Chapter 2), and points out alternative liming strategies for four rivers based on their characteristics. Relatively detailed plans are made for the rivers, and this should provide insight into liming techniques relevant for other rivers as well.

3. Liming Strategies and Techniques

Recommended liming strategies and liming techniques in this report are based on the Scandinavian experience with mitigation against acidified rivers during the last 20 years. In Norway liming started with coarse-grained liming material, as shell sand and gravel, for increased survival of brown trout in hatcheries and brooks. In some areas voluntary based liming was an important part of the fish management at the local scale in the 1960's and 1970's.

A liming program was initiated by the Ministry of Environment (MoE) in 1983. The program, being based on recommendations from a 5-year research project (Baalsrud et al. 1985), increased dramatically in size in the period 1993-1995, and has been at about 110 million NOK (20 million CAD) from 1996 to 2001. A similar development has been seen in Sweden, but the size of the program has been at a higher level for a longer period of time. The amount of money from the Swedish Government was as high as 200 million SEK (40 million CAD) in 2001.

Liming operation has been based on scientific knowledge. During the last 20 years a research and monitoring program has been run in parallel with the operational program. From the start this program has been financed by the MoE and organized through the Directorate for Nature Management (DN), with about 10% of the sum allocated for countermeasures. It stabilized at about 15 million NOK (2.5 million CAD) in the middle of the 1990's.

A national liming strategy should be closely linked to changes in acidification levels. This is done in Norway by dose regulation according to monitored pH-levels and evaluation of toxicity, and by calculation of existing and future critical load exceedances (Hindar et al. 1998). At present (2001) dynamic acidification modelling is used to get information on the timing of water quality improvements (Wright 2001) rather than end-point estimates.

A change has been seen in the liming strategy and in liming techniques over the last 10 –15 years (Hindar 1997). The change from liming of brooks and small lakes to larger lakes and river systems has introduced a more professional high-quality distribution and spreading system for limestone material. Lakes are limed with special equipped spreading boats. Limestone powder is mixed with lake-water and spread in a fan as the boat moves at slow speed along transects of the lake surface. In rivers, large lime-dosing plants add slurried limestone powder continously to the river. Doses are controlled by water flow and up-stream pH. In some dosing plants, doses are also controlled by downstream pH in a feedback system.

Terrestrial liming is an important part of the liming strategy in Sweden, but not yet in Norway. Research projects in Norway are currently gathering more information of aquatic and terrestrial effects. Liming of forested catchment is a promising option because the aquatic effects are optimal and changes in vegetation are limited. Data for six years after liming, and calculation with the acidification model MAGIC indicates that forest liming in Gjerstad, Aust-Agder County in Norway, will result in acceptable water quality for 50 years (Hindar et al. 2001). Inorganic aluminium was reduced to very low levels and pH increased almost immediately from about 5.0 to 6.0. No effects on forest vitality were documented. The particle size used in this experiment was 0.2-2 mm dolomite (not pelletized). The material was spread in the whole catchment, omitting surface water and bog areas.

Liming with coarser limestone products is limited to the spreading of shell sand and gravel on spawning grounds to improve the spawning substrate. Use of these products in rotating drums and liming wells is very limited.

In the following different liming material and liming techniques are characterised. Emphasis is on material and techniques that have “survived” in Scandinavia and on techniques that are supposed to fit a liming strategy in Nova Scotia.

3.1 Limestone materials and neutralisation reactions

Carbonates, oxides, hydroxides and industrial waste products have been used to neutralize acid waters (Sverdrup 1985; Dickson and Brodin 1995). The Norwegian Liming Project (Baalsrud et al. 1985) examined and evaluated potential deacidification agents. The recommendation was to use finely ground carbonates because these products are inexpensive, dissolve fast enough, and add buffer to the water. Hydroxides, oxides and waste products may increase pH to unacceptable levels (above pH 8.5) and may be harmful if not handled with care.

In the period 1985-2001 few other products were examined, but dolomite (Ca-Mg-carbonate) is now recommended for terrestrial liming because magnesium is supposed to prevent forests from Mg-deficiancy. Handling of inorganic Al is a challenge in Norwegian salmon rivers because Al may be toxic at low levels, and because acid tributaries run steeply into salmon producing parts of many rivers. Very short reaction time for inorganic Al exists if such tributaries are limed close to their confluence with the main river. Based on works of Birchall et al. (1989) tests with silica (SiO_2:NaO) have shown that inorganic Al may be detoxified at higher speed than if limestone powder is used (Kroglund et al. 1998).

The deacidifying and/or reactive properties of sea-water (Rosseland and Skogheim 1984, 1986), dissolved organic matter and groundwater have also been utilised in attempts to increase pH and/or detoxify Al (reviewed by Olem 1991).

Addition of phosphate (PO_4) may stimulate primary production in acidic lakes enriched in NO_3 (Davison et al. 1995). Assimilation of PO_4 removes significant amounts of NO_3 and adds OH^- ions to the water. The resulting increase in pH, e.g. from 5.1 to 5.6 (Davison, op.cit.) may reduce the solubility of Al and shift the Al-equilibrium towards less toxic Al-species. Phytoplankton biomass may increase to unacceptable levels, however, and result in a shift in the community towards blue-green algae.

In the following paragraph the main liming materials used are presented and references are made to systematic tests on chemical and biological water effects. The presentation is largely based on Hindar (1997).

3.1.1 Limestone powder

Calcite (calcium carbonate; $CaCO_3$) and dolomite ($CaMg(CO_3)_2$) as fine-grained powder may stabilize pH at intermediate levels (pH 6–8). Commercial products based on these minerals have low content of contaminants and are widely used for liming.

Carbonates dissolve in lakes as a function of pH, dissolved carbon dioxide, particle size distribution, available time and conditions for dissolution (Sverdrup 1985). Important reactions are:

$$CaCO_3\,(s) + H^+ = Ca^{2+} + HCO_3^-$$
$$CaCO_3\,(s) + CO_2 + H_2O = Ca^{2+} + 2\,HCO_3^-$$
$$CaCO_3\,(s) + H_2O = Ca^{2+} + HCO_3^- + OH^-$$

The dissolution is reflected in increased Ca, alkalinity, and thereby pH, and results in reduced solubility and thereby reduced concentration of inorganic Al in solution.

Particle size is the most important factor affecting dissolution. A small reduction in particle size distribution of the limestone material represents a significant increase in dissolution properties due to the relatively large increase in surface area available for chemical reactions. Pre-slurrying of the limestone material increases the effective particle surface due to deaggregation of particles and thereby increased dissolution rates (Sverdrup and Bjerle 1982; Molot et al. 1986).

Dissolution in lakes may be separated into an initial phase and a long-term dissolution phase. The initial phase lasts as long as particles are in suspension after liming. Time available for dissolution is governed by lake depth; greater depth results in more complete dissolution. Long-term dissolution of sedimented limestone powder may contribute significantly to the liming effect, stabilises the water quality and may therefore increase the duration in some lakes. Dissolution rates of about 0.4 t ha^{-1} yr^{-1} after ordinary lake liming with relatively high dosages and 2.5 t ha^{-1} yr^{-1} after shore liming have been reported (Rosseland and Hindar 1988).

The limestone dissolution is fairly high after lake liming (Sverdrup 1985; Henrikson and Brodin 1995), especially if very fineground material is used (> 95 %; Wright et al. 1996). Unpublished data from the world's largest lake liming project, the liming of Lake Nisser in Norway in the late autumn of 1996 (A. Hindar, unpublished data), indicates 100 % instant dissolution of 10,000 tonnes of calcitic powder (86 % $CaCO_3$; particle size distr.: 90%<70 µm; 50%<19 µm; 20%<4.5 µm). This result may be ascribed to low doses (pH increased to 6.0), pre-slurrying of the material upon application, a mean lake depth of 93 m and circulating water in combination with wind exposure during liming.

Mechanical forces are important for dissolution in rivers. Turbulent waters decrease the boundary layer[1] around the limestone particles, crush coarse particles into smaller and thus increase the total reactive surface of the particles. Time available for dissolution is increased if more rapid water flow allows the particles to be transported down the river rather than sedimented. Floods may resuspend sedimented particles, thus increasing the dissolution. Lime dosing may result in high dissolution, and instant dissolution of 60-80 % has been reported (Sverdrup 1986a; Simmons and Cieslewicz 1996; Zurbuck et al. 1996). Zurbuck et al. (1996) stated that 100 % dissolution is likely if the additional dissolution of sedimented calcite is included. In this case very fine-ground slurry (mean particle size of 3 µm) was produced.

Both water quality and flow affect dissolution. At base-flow, pH is often relatively high and a large fraction of the limestone material may be sedimented close to the point of application (Hindar 1987). At high flow, both decreased pH and increased turbulence ensure more complete dissolution (Zurbuck et al. 1996).

Delayed dissolution is advantageous when dosing operation stops for some reason. Ca adsorbed to minerals or organic surfaces on the streambed, especially mosses due to the surface area, is of significance also in unlimed streams to dampen drops in pH (Wathne and Røgeberg 1988; Norton et al. 1992).

Warfvinge (1986) found that dissolution of calcite in soils is dependant on the calcite dose relative to the exchangeable acidity of the soil, the particle size distribution of the liming material, the soil water content, deactivation reactions and the mass transfer coefficient for the H-Ca ion exchange reaction. pH, CO_2 partial pressure and flow rate through the soil profile was of less importance. Thus, dissolution conditions on soil and bog surfaces are different in many respects from conditions in surface waters.

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[1] The boundary layer is a region of stagnant solution around a particle. In stagnant water the thickness of this layer will be large whereas in stirred systems, like streams, the layer will be 10-30 µm. The size of the boundary layer determines the rate of diffusion and thus reaction rates at the particle surface.

Recent terrestrial liming experiments in Norway have shown that a stable water quality may be produced, even in periods with heavy flow (Traaen et al. 1997; Hindar et al. 1996). Calculations indicate that forest liming and liming of heath-land in Norway result in an annual Ca-transport (and Mg-transport in the case of dolomite) of about 1-2 % of the lime-dose (Hindar et al. 2001). Once stabilised the transport seems to be of this size for more than 10 years. The particle size used in these experiments was 0-0.2 mm calcite and 0.2-2 mm dolomite (not pelletized), respectively. The material was spread in the whole catchment, omitting surface water and in recent studies also omitting bog areas and barren rocks to prevent damage on mosses and lichens.

Experiments with liming only on bogs are few in Norway but wetland liming is a part of the operational liming practise in Sweden. The effects on water quality are very good (Hindar et al. 1996) but the wetlands have to be relimed relatively often as the effect may last 2-3 years. To minimise negative effects (dieback of Sphagnum mosses) and to reduce the total amount of lime, annual liming is preferred in Sweden.

3.1.2 Shell sand and gravel

Also, more coarse liming material, such as shell sand and gravel of calcite and dolomite is used. Few systematic experiments have been conducted, however, but some reviews are available and technical reports exist. This presentation will therefore be more summarised than the presentations above.

Shell sand and gravel may be spread on the river bed. The aim of such application (in Norway) is usually increased reproduction of brown trout in brooks and small rivers. The experience after liming with these products is in general that liming improves the fish populations, but the reason why is not fully understood. Examination of several locally organised liming projects which use shell sand or gravel indicates that the applied doses vary (Barlaup et al. 2001).

Characteristic water chemistry downstream of limed areas is significantly increased pH and Ca, and reduced concentrations of inorganic Al at low and moderate water flow. No or insignificant effects on these parameters are found at high water flow (Watt et al. 1984; L'Abée-Lund et al. 1985; Lacroix 1996). However, a significant and probably very important increase in water quality of the interstitial water (water below the surface of the stream bed) is found (Mayhew 1989; Barlaup et al. 2001). Increased pH and Ca and reduced Al in the environment where eggs and yolk sac fry live may be important for increased survival during snow melt. Lacroix (1985) found a close relationship between hatching success for salmon embryos and mean pH of the interstitial water. Alevins may benefit from the increased stream water quality at low and moderate flow after swim up and refuges may be found at the bottom or in stillwaters when the water flow increases after rainfall.

Coarse liming materials applied directly on the stream-bed should thus be regarded more as a remedy to improve the spawning substrate than the stream water quality itself. These liming materials have also been used in diversion wells and rotary drums, see later paragraphs.

3.1.3 Calculation of doses

Calculation of lime doses must take into account the water chemistry, the dissolution conditions, the limestone material for lakes and the time period until reliming (Sverdrup 1985). For typical acidified lakes and streams H^+, cationic Al and dissolved organic substances are neutralised or deprotonated. Contribution to acidity from H^+ often dominates in acidic clear-water but in colored waters dissolved organic acids contribute significantly. Given a charge density of at least 5 µeq mg^{-1} TOC, a concentration of 6-7 mg L^{-1} TOC represents as much or more acidity (> 30-35 µeq L^{-1}) as H^+ (32 µeq L^{-1}) in a clear-water lake of pH 4.5. In special cases, such as in runoff from mines, oxidized bogs or blasted sulphide-containing bedrock, deprotonation of large amounts of Al may be the dominating lime-consuming reaction (Hindar and Lydersen 1994).

Estimation of lime dosage may be based on measured water chemistry, titration with e.g. hydrogen bicarbonate or an empirical pH-Ca-relationship for lakewater. Of these three options titration represents the most precise method if reactions in the sample are allowed to go to completion.

Dissolution varies according to pH, water depth (lakes) and turbulence (rivers). However, particle size distribution is the single most important factor controlling dissolution (Sverdrup 1983, Sverdrup et al. 1985). Temperature is of less importance than the mentioned factors. Dose calculation must be corrected for dissolution rate according to these factors.

In lakes, catchment size, specific runoff of the area and lake retention time are key factors for estimation of the total requirement of limestone material. Data programs (Sverdrup 1985; 1986b; de Pinto et al. 1989; Håøya et al. 1996) handle these factors and facilitate precise calculations of reacidification rates. However, significant deviations from average runoff regimes may result in longer or shorter liming intervals than calculated.

Lime dosages for rivers are more difficult to calculate than for lakes due to the variability in water quality and runoff both within and between years. If no dose-regulating system is used, fixed-doses for expected high acidity are often used in order to prevent undesirable decreases in water quality. In periods of more favorable water quality such fixed doses will increase pH beyond target levels.

Doses for wetland liming depend on runoff pH, the limed area relative to total catchment area and liming frequency (Warfvinge 1986). Hydrological characteristics of the limed area are also important. At Røynelandsvatn a dose of 20 t ha^{-1} in a bog area corresponding to 4 % of the catchment area was adequate to increase pH from 4.5 to above 5.5 for 2.5 years (Hindar et al. 1996).

Whole-catchment liming of forested and non-forested areas has shown that doses of 1-3 t ha^{-1} of 0-2 mm calcite or dolomite may result in a long-lasting acceptable water quality (Traaen et al. 1997; Hindar et al. in prep). 1-2% of the applied Ca and Mg was transported out of the catchment annually. In the liming experiment at Tjønnstrond, carried out in 1983 and still (2001) monitored, this transport is almost constant, underlining the long-lasting effect.

A model based on the critical load exceedance has been developed for dose calculations on a catchment and regional scale (Hindar et al. 1998). Scenarios for future liming needs were estimated based on present and expected S and N deposition. The total limestone requirement and costs were calculated for a 1850 km^2 salmon river catchment and Norwegian counties. This is supposed to facilitate long-term nature management in acidified areas.

3.2 Liming techniques

A summary of the main principles of the three main liming techniques is presented, followed by descriptions of diversion wells and rotary drums.

3.2.1 Lake Liming

Lakes may be limed by direct application on the surface either from a spreading boat or from helicopter (**Figure 1-Figure 3**). Finely ground particles (0-0.2 mm) is required for acceptable dissolution before the limestone particles reach the lake bottom. The best way of spreading is by applying limestone powder as slurry after mixing with lake-water. Spreading the slurry in a fan ensures maximum dissolution as the particles de-aggregate and the concentration of the particles is kept as low as possible in the water.

Spreading by helicopter reduces the dissolution because the material is spread dry and tends to reach the lake surface as aggregates and in large concentrations.

Liming only on the lake surface may result in reacidfication of shore areas during wintertime, when acid meltwater enters the lake and flows like a stream below the ice-cover. This may reduce spawning success for lake-spawning fish species (Barlaup et al. 1998).

Figure 1. Lake liming. Limestone powder is transported by trucks to the lake, pumped to the spreading boat by air pressure, and then to the lake mixed with lake water to a slurry. (scanned with permission from http://www.norcem.no/kalk/).

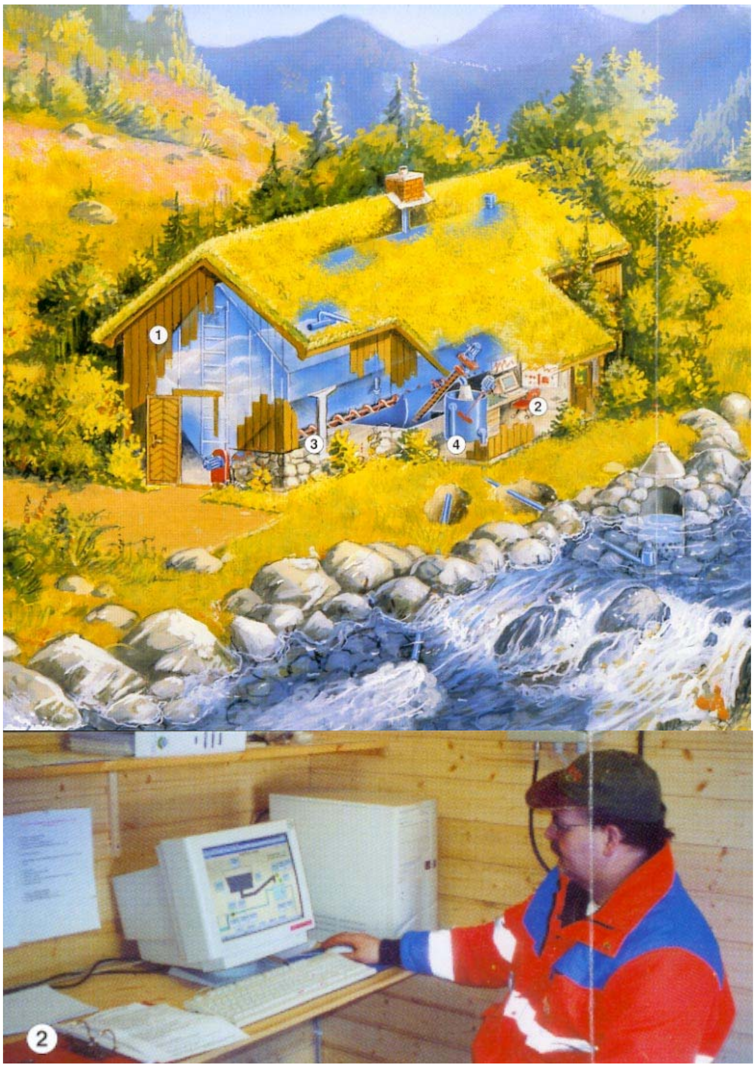

Figure 2. Modern technology together with nature and local building tradition creates living rivers. (scanned with permission from http://www.norcem.no/kalk/).

3.2.2 Lime Dosing

Rivers and larger streams may be limed with use of lime dosing plants (**Figure 2**). The principle is to add limestone powder as a slurry by mixing with circulating water from the river. Mixing of dry powder to slurry increases the dissolution by deaggregating particles before they reach the river water.

Dose regulation is by water level (most important) and/or pH-signals from upstream and/or downstream of sensors. In rivers with changing pH, caused by natural variation or upstream liming, dose regulation by pH may be important and reduces the total liming cost.

Continuosly dosing of limestone powder is a challenge due to humidity that tends to clogg the particles. Particles may aggregate, settle, and result in mechanical problems. Advanced electronic devices are part of the flow- and pH-controlled dosing plants, rendering them sensitive to disturbances by lightning in exposed areas. However, such problems have been less frequent as the technology has improved over the years.

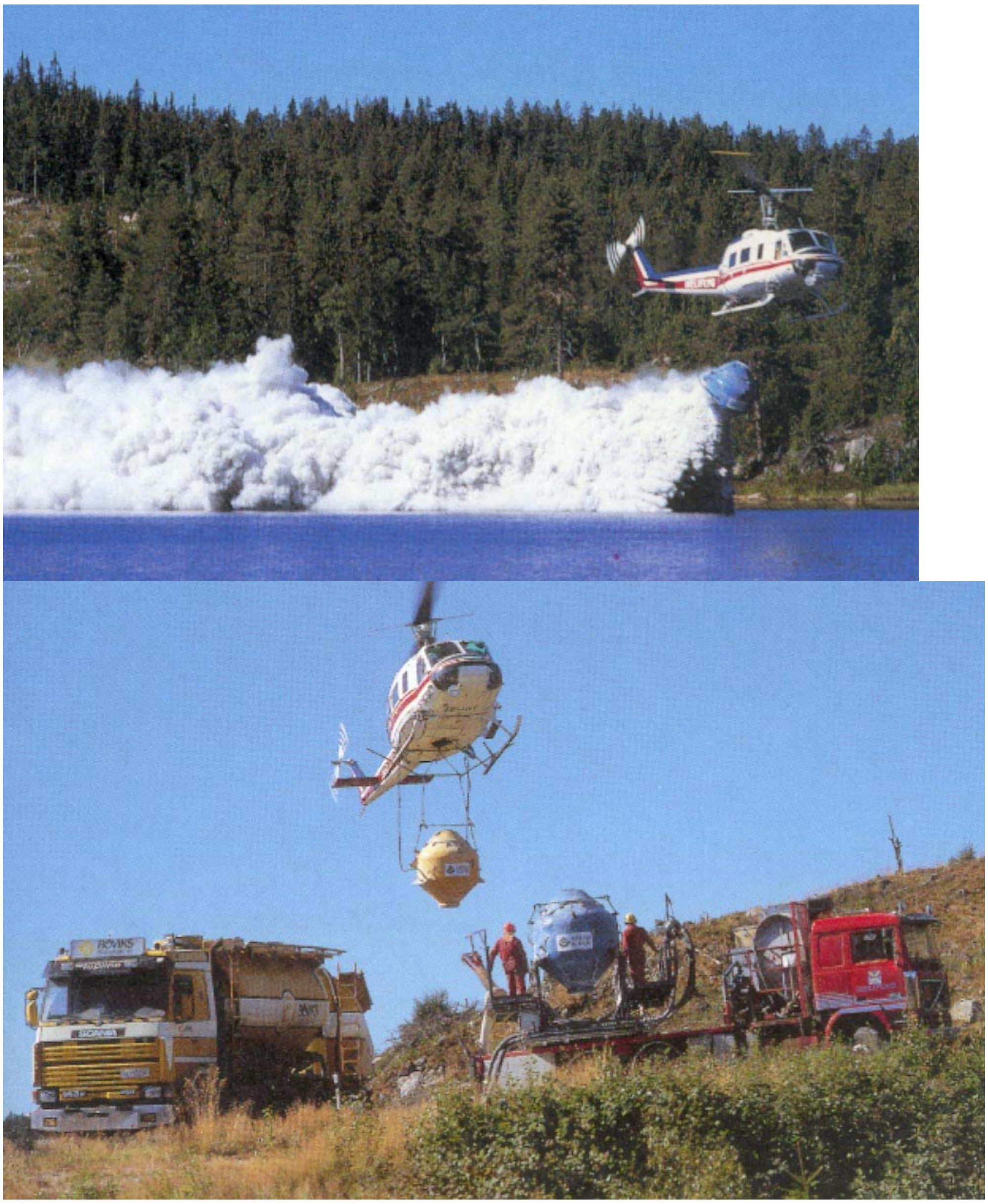

Figure 3. Liming with use of helicopter. One container is filled with limestone powder while the other is transported to the lake or catchment. (scanned with permission from http://www.norcem.no/kalk/).

3.2.3 Terrestrial Liming

Liming of terrestrial compartments is carried out by use of helicopter (**Figure 3**). Fixed doses are spread evenly over the desired parts of the catchment. As the idea is to apply liming material on land, surface waters are omitted in these operations. Also, sensitive parts of the catchment, such as wetlands (if regarded as valuable) and barren rocks, may be omitted.

The somewhat more coarse-grained limestone particles are fed from the truck with airpressure or from bags by gravity to a container, which is carried by the helicopter. The material is spread dry by centrifugal force or by opening a slot on the underside of the container.

3.2.4 Other liming techniques

Diversion wells (**Figure 4**) are (or rather should be) based on the principle that shell sand or gravel is kept in a fluidised lime-bed system (Sverdrup et al. 1981; 1985) within a vertical cylinder. The power from a water current keeps the sand or gravel in motion. In this way coarse particles will be grinded to smaller particles, which eventually dissolve and neutralise the stream water.

Relatively low-density shell sand in diversion wells will easily float and be transported out of the container if the water current is too strong. If the water current is too weak most of the particles will stay calm and the well will function more like a filter for water. Neutralization may then be greatly reduced.

The specific gravity of gravel is higher than for shell sand and this requires a stronger current for the gravel to be kept floating (Sverdrup et al. 1985). This will only be achieved if a sufficient part of the stream is fed into the container from a certain height, e.g. from a dam.

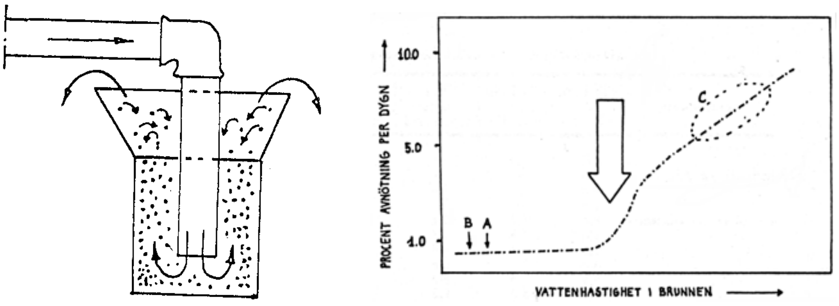

Figure 4. Diversion wells (left) are based on the principle that gravel is kept floating in a strong water current, crushed to small particles, and then dissolved. A certain amount of the stream water may be neutralized if this is achieved. The curve (right) is based on the relation between water flow inside the well (x-axis) and percent of content crushed to small particles per day (y-axis). Many wells are characterised by being along the lower left part of the curve (A and B), whereas recommended area is represented by the C in the upper right part of the figure. (scanned from Sverdrup et al. 1981).

The deacidification potential for a single well is relatively low and a large part of the stream (more than one third) should be led through the system. Such wells operate at a critical current velocity inside the well (Sverdrup et al. 1981), and will not adjust lime doses according to changes in stream flow. At least two wells, which may be triggered at different water level in the stream, are required to compensate for the fixed doses that are produced in the well.

The experience with diversion wells is not very good. This is due to the requirement of a sophisticated feeding system for two or several containers, as described above, which in most cases not has been built. The main reason for that is the non-professional, rather a trial and error-based construction by enthusiasts of these systems, as noted by Sverdrup et al. (1985).

Relatively high construction costs (if built according to controlling parameters) and many man-hours from volunteers for filling liming material and look after the wells are required to ensure continous neutralisation. These systems are in principle good alternatives and based on inexpensive liming material but seem to fall between simple systems that require a minimum of efforts (spreading on stream bed) and advanced systems for larger rivers that may be handled by professionals.

4. Materials and Methods

4.1 The Southern Upland Area

The southern upland is characterised by being relatively flat, covered either by dense, and in many areas shrublike, coniferous, decideous and mixed forests or peat and wetlands. Muskegs are also common representing open peat-land with stunted tree growth. No parts of the catchments are above the timber line, and the highest hills are at about 300-400 m above sea level.

Underlying bedrock in LaHave and Medway catchments are slates, greywacke and granites (Watt et al. 1983). An almost continous cover of shallow glacial tills, with frequent drumlin and moraine deposits (Clair and Freedman 1986) allows for the dominance of forest cover and wetlands.

Annual mean precipitation of the area is about 1400 mm.

Sulphate deposition was 34±5.2 meq m^{-2} yr^{-1} in the Kejimkujik National Park, close to Medway river, in the period 1980-1990 (Shaw et al. 1995), and decreased from 32.4 to 21.4 meq m^{-2} yr^{-1} from 1983 to 1997 (Clair et al. 2000). Nitrate depostion was about 16 meq m^{-2} yr^{-1} in the period 1983-1997 (Clair et al. 2000).

4.2 The Rivers

The work has been based on field-work and existing data from four rivers of the Southern Upland region of Nova Scotia, Canada (**Figure 5**). **Table 1** summarises catchment and hydrological characteristics, while more detailed data are presented in **Table 2**.

Table 1. Data for catchment areas, specific discharge, and runoff for rivers. Also shown is pH classification according to Watt (1997). Class B (remnant salmon population) and C (salmon population depleted only in smaller tributaries) is pH-range 4.7-5.0 and 5.1-5.4, respectively.

River	pH class	Catchment, km^2	Spec.discharge, L s^{-1} km^{-2}	Runoff, mill.m^3/year
East River, Sheet Harbour	B	577	38.5	700
West River, Sheet Harbour	B	262	38.5	320
Medway River	C	1468	29.7	1380
LaHave River	C	1602	27.5	1390

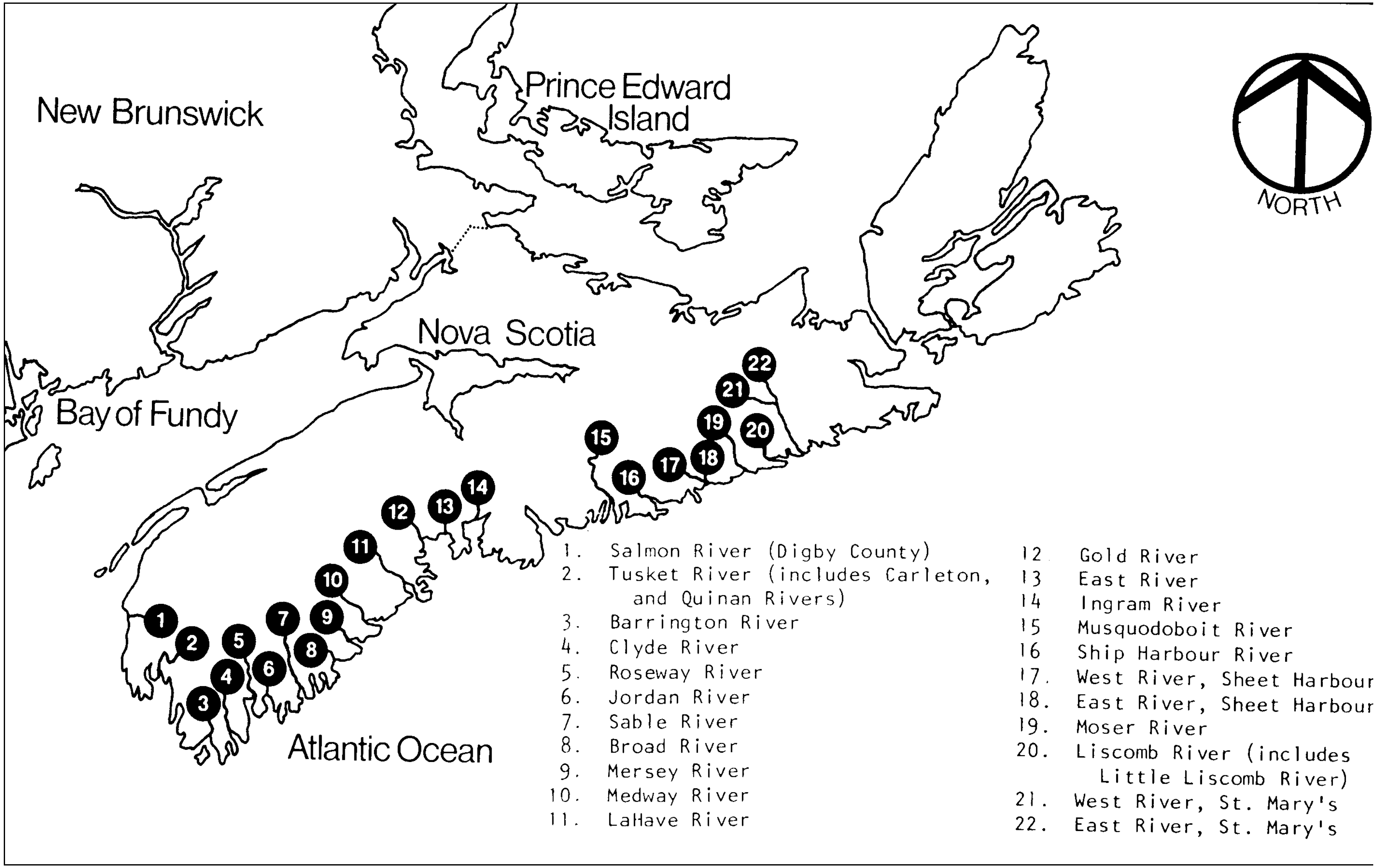

Figure 5. Nova Scotia and two other Atlantic Canada provinces. Location of acidified rivers in Nova Scotia is shown. Medway and La Have River are about 100 km west of Halifax, and are numbered by 10 and 11. West and East River, Sheet Harbour are about 100 km east of Halifax, and are numbered by 17 and 18. (From Farmer et al., 1980).

The rivers are characterised as follows:

East River, Sheet Harbour, is characterized by being divided into several relatively large tributaries. Beginning in the western part, Seven Mile Stream, Twelve Mile Stream and Fifteen Mile Stream run parallell towards south-east and forms the main river, which runs southwards to Sheet Harbour. In-between in the upper part is Ten Mile Stream and Seventeen Mile Stream.

Large headwater lakes are few, only Governor and Seloam Lake. Como Lake, Mulgrave Lake and Marshall Flowage in the middle and lower part of the catchment have short water-retention times.

The area is characterised by dense forests in a relatively flat landscape. Overview is difficult from the ground and access to rivers and lakes is largely by the many roads that have been made for transporting logs out of the forest or for access to dams at lake outlets.

Although there is access to most parts of the catchment, settlements are few and residents are found only in the Malay Falls area and at the outlet in Sheet Harbour.

The river is regulated by Nova Scotia Power. Dams for control of water flow to the two power stations are built in Governor Lake (head-water in Twelve Mile Stream), Seloam Lake (head-water in the upper north-east), Anti Dam (Fifteen Mile Stream), and in the Malay Falls and Ruth Falls in the lower part of the river.

At both Anti Dam and Malay Falls fishways are missing, making salmon access to upstream areas impossible. A fishway is constructed at Ruth Falls, however, and fish from the fishtrap here are used as brood stock for production of juvenils. Salmon smolts are allowed to pass downwards through the dams at Anti Dam and Malay Falls.

Governor Lake has been limed, but not the last four years (1998-2001) due to un-safe ice-cover during the relatively mild winters experienced in this period.

West River, Sheet Harbour, is a smaller and less forked-like catchment than East River, but still divided in three main tributaries; Killag River in north, West River (the main river) in the middle and Lake Alma/Little River in south. Only Lake Alma of the headwater lakes is of some size. In the lower, northern part Rocky Lake is of moderate size.

As in East River, the catchment is flat with maximum hight above sea level of about 200 meters. Also here the forest is used in the paper and pulp production industry.

This river is not regulated for hydroelectric power production.

LaHave River is different from the Sheet Harbour rivers in being larger and more densely populated. It resembles East River by being highly divided into subcatchments.

Except for Sherbrooke Lake in the eastern part and Big LaHave Lake in the western part the catchment is characterised by a lack of larger lakes that may be suited for lake liming. Sherbrooke Lake has or had a unique population of lake trout (*Salvelinus namaycush*), one of the very few in Nova Scotia, which may warrant careful attention. The water quality may be a problem but this is not yet clarified.

The western part of LaHave River, some of which joins the main river at New Germany (West River) and some further downstream (West LaHave River), is more acidic than the rest of this catchment. Countermeasures in these tributaries are supposed to be sufficient for improving the salmon population of LaHave River. The tributary from Scrag Lake (Little River) downstream of Big LaHave Lake is an extremely acid and fishless tributary, which used to give good catches of brook trout.

Medway River is, like the western part of LaHave River, very acid. Settlements are found in all parts of the catchment except for the upper western part around Lake Alma.

The river system is divided into two main branches; Pleasant River in east and the main stream in west. The Tupper Lake system is in-between these. The Cristopher Lakes system at the lower western part runs into Ponhook Lake. Ponhook and Molega lakes are large lakes in the middle of the river system and the whole of their combined catchments drains to the Ponhook Lake outlet. The small lakes in the lower, eastern part, north of the highway from Liverpool to Halifax, are also acid.

The forest in some of the catchment is utilized for paper and pulp production in the large paper mill in Liverpool at the outlet of the Mersey River west of Medway River.

4.3 Available data

To get good estimates on lime doses data on water chemistry from these river systems should ideally cover all major tributaries, lakes and main rivers for some years. Data should be from monthly sampling in streams and rivers and from sampling 2-4 times a year for lakes, depending on water retention times. These requirements are not fulfilled, although some exceptions should be mentioned (East River, Sheet Harbour and West River of the La Have River system), and make the evaluation of acidity problems difficult and calculations uncertain for several localities.

For the few localities with more extensive data sets (e.g. East River, Sheet Harbour; data from Nova Scotia Power), large seasonal variation in pH has been noticed. pH may be very low (at about pH 4.5) in high-flow periods and relatively high, also above target levels, in the summer season. As dose calculations are on a yearly basis, this variation has to be taken into consideration. Lime dosing may be shut down in periods with acceptable water quality.

For localities without sufficient data the extensive survey by Gilles L. Lacroix at DFO, St. Andrews of all the four river systems on seven occasions in 1996-1997 has helped identify acid tributaries on basis of pH measurements.

Relevant morphometric and hydrological data for lakes, streams and rivers are given in the Appendix.

Mean depth was calculated for all lakes on basis of volume and surface area. Water retention time for the lakes was calculated on basis of volume, catchment area and specific runoff.

No data existed on volume and max depth for Big LaHave Lake and Alma Lake (Medway). Volume was estimated on basis of surface area, anticipated max depth of 20 and 15 m, respectively, and a constructed, traditional shape of a deep to area (hypsograhic)-curve. The area below the curve was integrated. Mean depth was calculated at 5.9 and 5.0 m, respectively.

A summary of data for the most important lakes considered for liming in the four catchments are given in **Table 2**.

Table 2. Data for the most important lakes considered for liming in the four catchments.

Locality	**Lake surface, ha**	**Mean depth, m**	**Catchment, km^2**
East River, Sheet Harbour			
Governour Lake	652	2.9	27.4
Seloam Lake	291	3.2	20.0
West River, Sheet Harbour			
Lake Alma	440	3.1	17.8
Rocky Lake and others	-	-	30
LaHave River			
Big LaHave Lake	440	5.9*	39.5
Medway River			
Alma Lake	271	5.0*	95.5
Shingle Lake	461	2.0	49.1
Molega Lake	2168	4.6	339
Ponhook Lake	1595	-	1096

* based on best guess of max depth and constructed hypsographic curve.

4.4 Water Quality Requirements and Mitigation Targets

The combination of slowly weathering bedrock, dense forests and bog-areas results in a special type of water quality of lakes and rivers; highly colored and very poor in dissolved ions. The high organic content is both undesired and an advantage according to water quality requirements for Atlantic salmon. Dissolved organic substances are mostly weak acids and produce low pH, which renders the water vulnerable for additional acid input. At the same time aluminum is complexed by the organic substances.

Opposed to rivers in many other acidified areas this is why the water chemistry of rivers in Nova Scotia is not characterised by toxic levels of inorganic aluminum. This has been shown by bioassays (Lacroix and Townsend 1987; Lacroix 1989; Peterson et al. 1989), and population estimates (Lacroix 1989). Inorganic concentrations of aluminum are usually < 50 µg L^{-1} (DFO 2000). However, natural and anthropogenic acidification results in pH of many rivers below levels that can sustain a self-reproducing population of Atlantic salmon.

In western parts of Scandinavia toxic levels of aluminum may occur at relatively high pH-levels, and target pH of limed rivers is between 6.0 and 6.4, depending on content of organic substances and life stage of salmon. Highest target levels (pH 6.4) are in rivers with low organic content (TOC or DOC < 3 mg L^{-1}) and during the smoltification stage, the most sensitive life stage of Atlantic salmon in acidified, Al-rich waters.

Studies in Nova Scotia strongly indicate that a pH of 5.4-5.5 will ensure self-reproducing populations of Atlantic salmon, as there are no signs of decreased population size or catches above this level. In the pH-range 4.7-5.4 negative effects should be expected, and rivers with lost salmon populations are characterised by having pH below 4.7. Lacroix and Korman (1996) showed that episodes of acid water were critical for salmon smolt production. According to ASRAM (Atlantic Salmon Regional

Acidification Model), small increases in pH (0.2-0.4 units) would lead to large relative increases in smolt production and to population recovery.

All four of the examined rivers have important salmon producing tributaries, resembling rivers in the UK. In contrast a typical salmon river in Norway is characterised by having a dominating part of the salmon production in the main river, and by large tributaries in areas upstream of the parts that are accessible to salmon. In East River, Sheet Harbour the potential for a self-reproducing salmon population is influenced by limited access for upwards migrating spawners, however. Whereas liming for salmon in Norway can focus on reaching target pH-levels in the lower, anadromous part, liming of Nova Scotian rivers should aim at reaching target pH-levels also in tributaries and in some areas at relatively long distances from the river mouth.

Of these reasons we have set target pH at 5.5 for all liming operations, meaning that pH should never fall below this level in limed lakes and river sections. A more sophisticated way would be to combine anticipated salmon population response to different pH-targets with cost estimates for achieving these pH-targets (Power 1998), and then use this as a basis for recommendations regarding pH-increase.

Lake and river liming has to consider dilution, either by acid inflow (lakes) or acid tributaries downstream of lime dosing (rivers). Resulting pH after liming of lakes or at dosing sites will therefore be considerably higher (pH of 6-7) than the limit of pH 5.5. In general, no harmful effects have been associated with these higher pH-levels, but sedimentation of limestone powder at spawning sites or important production areas for fish and invertebrates should be avoided.

Although the main aim of liming is to increase pH above critical levels another important aim is to keep pH-levels as low as possible reasons of cost; enough is enough, more than enough is a waste of money. Ecological and economic optimisation has been established as part of the general guidelines for liming in Norway.

Liming may produce acceptable water quality and thereby increase the possibilities of both salmon production and an expected composition of fauna and flora. However, rivers and catchments are subject to exploitations that may be disadvantagous for salmon, and attempts should be made to co-ordinate liming with other efforts to reach the salmon producing potential.

4.5 Dose-calculation

Lime doses were calculated on the basis of water chemistry of the river or lake and pH targets, see Appendix B. Dose calculation included contribution to lime requirement from H^+, alkalinity and TOC. Aluminum was supposed to be organically complexed and was not included.

Many of the data series indicate episodes of very low pH compared to what may be the more “normal” situation. The calculations are based on typical low-pH situations but not the extremes. pH data were scarce or were found to vary to such an extent that a fixed increase of 0.5 unit in target areas (from 5.0 to 5.5) was used in many of the calculations. This increase also holds for West River (data from Watt et al. 1996) and for East River, Sheet Harbour (data from N.S. Power). Based on data from these rivers, TOC from all sites was supposed to be in the range 5-10 mg L^{-1} (7 mg L^{-1} chosen as representative).

A “titration curve” from pH 4.5 to pH 6.5 was then constructed for the relationship between pH and theoretically calculated $CaCO_3$ -increase for single pH-steps. $CaCO_3$ requirement was found by taking the difference of the $CaCO_3$-concentration corresponding to target-pH and pre-liming pH. The content of $CaCO_3$ in the limestone material was supposed to be 90 %, and the dissolution in lakes was set to 50-80% depending on pH and mean depth. Liming of shallow lakes with relatively high pH will result in lower dissolution than liming of deep lakes of low pH. Long-term dissolution (until reliming) was included in the figures. Limestone dissolution in rivers was set to 70 % as annual mean, lower (50 %) in smaller streams. Dissolution rates are very difficult to estimate, especially in rivers, and should be regarded as suggestions, rather than exact figures. Dissolution will be low in periods with low flow, and the limestone material may easily sediment to the stream bed.

If the $CaCO_3$ content of the limestone material, which actually is being used, differs from 90 %, this should be corrected for. Also, measured dissolution rates may be incorporated into the calculations.

Water retention time in lakes, dissolution conditions in streams and rivers, and costs are dependent on hydrological characteristics. Due to large variation between years and the problems related to vertical mixing in lakes during winter, variation in hydrology introduces significant uncertainty for dosage calculations.

Specific discharge ($L\ s^{-1}\ km^{-2}$) for the four rivers was calculated on the basis of data records from LaHave River at West Northfield, Medway River at Charleston, Liscomb River at Liscomb Mills (40 km east of Sheet Harbour), and Musquodoboit River at Crawford Falls (50 km west of Sheet Harbour). Data records were from the periods 1915-1990, 1915-1990, 1962-1988, and 1915-1988, respectively, and were given as monthly means and annual means. The numbers were as follows; 27.5, 29.7, 40.6, and 36.5 $L\ s^{-1}\ km^{-2}$, respectively for these four rivers. Specific discharge for the two rivers at Sheet Harbour was taken as the average (38.5 $L\ s^{-1}\ km^{-2}$) of the numbers for Liscomb River and Musquodoboit River.

Differences between years of the specific runoff introduce large uncertianties in the estimates of yearly runoff, retention time and limestone powder requirements. This is why a relatively simple approach to pre-liming water chemistry may be justified.

4.6 Limestone in Nova Scotia

The Mosher Limestone Company Ltd in Musquodoboit produces 50485 tons (45800 metric tonnes) of limestone a year and has 22 employees according to their web-site. The company produces agricultural grade dolomitic limestone in its grinding plant at Upper Musquodoboit. The product is bagged or supplied in bulk for distribution throughout the Atlantic Provinces.

The company was visited as part of this work. The company had access to both calcite and dolomite and would produce the limestone powder quality required for lake and river liming. Higher production costs for finer ground powder will most probably be more than compensated for by increased dissolution in water.

We also mentioned the possibility of a co-operation between limestone companies in Norway and Mosher, and got the impression that this would be interesting. Co-operation may be on liming techniques such as spreading systems for boat and helicopter and dosing systems for lime dosing plants.

5. Recommendations

5.1 General assumptions

The water quality target for salmon was set at pH 5.5. No reduction of population size or catch is found above this pH-limit in Nova Scotia rivers (Watt 1997). Based on the work of Lacroix and co-workers we anticipate that survival of salmon is not limited by toxic aluminum. This is due to relatively high concentrations of dissolved organic matter. Humic substances complex with aluminum and form non-toxic complexes.

Most of the catchments of the four Nova Scotia rivers in this work is within 50 km off the coast. Hindar et al. (1994, 1995) found serious problems with Al-mobilisation at some distance from the coast of several rivers along the west coast of Norway during a sea salt episode in 1993. Similar problems may exist in Nova Scotia, but no documentation has been found in the literature. Similar effects of sea salt deposition have been found in Maine, US (Heath et al. 1992). At present, we do not take this into account, but recommend monitoring to reveal if sea salt depostion may cause harmful effects in some parts of the rivers. This may influence the liming strategy.

Recommendations are based on the following characteristics for limestone powder for lake and river liming; 90% as $CaCO_3$; 90% < 0.1 mm, 50% < 0.01 mm and 20% < 0.002 mm. Deviation from this $CaCO_3$ content may be corrected for directly. Another particle size distribution may be corrected for by use of diagrams presented by Sverdrup (1983). Instant dissolution in lakes (before particles settle to the bottom) is based on these diagrams. An additional 20% dissolution is set for long-term dissolution (until reliming). Dissolution in rivers is based on a diagram presented by Sverdrup et al. (1985).

Dissolution as percent of dose after lake-liming is based on summer/autumn-liming from spreading boats, which means that limestone powder mixed with water is spread on the lake surface in June-October. Helicopter liming of lakes and liming on ice may significantly reduce the dissolution efficiency due to clogging of particles.

Terrestrial liming by helicopter should be carried out in late autumn (October) to reduce negative impacts on vegetation. Liming on snow or on frozen soil will probably result in larger loss by runoff and reduced long-term effect, but no documentation exists.

Dose calculations are based on annual averages in water chemistry or typical low-pH situation but not the extremes. Bearing in mind the great seasonal variability in pH and TOC related to water flow (Clair and Freedman 1986), this simplification may underestimate doses in certain periods and overestimate doses in other periods. However, lime-dosing plants in rivers may be regulated according to pH and thereby take this variability into account. If pH is not part of the dose control system the lime dosing plant may be set to operate only in periods with critical water quality. This requires monitoring of upstream pH.

Liming needs on an annual basis are calculated by use of mean discharge. The variability in discharge between years will thereby represent an uncertainty in the estimates of annual dose and the liming cost.

This report does not include cost estimates other than rough figures for equipment. High-quality dosers for large rivers cost about 2.5 mill. NOK (400.000 CAD) and medium-sized dosers cost about 1 mill. NOK (150.000 CAD). The spreading boat, as shown in this report, costs about 2 mill. NOK

(300.000 CAD). Production costs may be high in Norway compared to Nova Scotia. Cost of liming material will depend on particle size of the material and transport.

The paragraphs below present both possibilities and limitations for liming of each river systems. Among several approaches the recommended strategies are supposed to give the greatest net benefits. If one decides to make one change in the recommended strategy others should follow to get the same overall effect on water chemistry and thereby on the Atlantic salmon and other sensitive organisms.

5.2 East River, Sheet Harbour

5.2.1 Possibilities and limitations

This river is characterized by being regulated for hydroelectric power production, very low population density and lack of electricity in large parts. Many of the roads are seasonal and access may be limited. The river system is widely divided in the upper half of the catchment, and few lakes have long retention times. The main river is dominated by storage reservoirs and dams in the lowermost part.

A fishway for upwards migrating salmon does exist, but only at the outlet of Ruth Falls Flowage. This limits the possibilities for having a self-reproducing salmon population in this river, and the salmon production is dependent on hatchery-produced stocking material. Bypass for downward migrating smolts exists at the power production plant at Malay Falls and at the outlet of Marshall Flowage further upstream.

East River is suited for liming, but the power production will limit the possibilities for a self-sustained salmon population.

Liming of Governor Lake and Seloam Lake, lime dosing in Seven Mile Stream, Twelve Mile Stream, and Fifteen Mile Stream, and terrestrial liming of Grant River is recommended.

Lime dosing will thus be the dominating liming technique. This may be a challenge in this river as electric power is nonexistant at the dosing sites and due to possible access limitation for trucks during the winter period. A successful liming project will therefore be dependent on one or several service people and cooperation with Nova Scotia Power.

5.2.2 Recommended strategy

The suggested liming sites are shown in **Figure 6**.

Liming of Governor Lake.
Governor Lake has a water retention time of 0.6 yrs and is therefore suited for lake liming. pH was approximately 5.0 and the lake should be limed to pH> 6.0, thereby increasing the water quality at the outlet and downstream of the suggested lime dosing plant in Twelve Mile Stream to pH> 5.5. To achieve pH> 6.0 until reliming the Ca-increase after liming should be 4.0 mg Ca L^{-1} as dissolved Ca. Based on this increase in Ca, dilution according to the retention time, and long-term dissolution of sedimented limestone material the lake should be limed with 353 metric tonnes once a year.

Liming of Seloam Lake.
Seloam Lake has a water retention time of 0.4 yrs and is therefore moderately suited for lake liming. pH was approximately 5.4 and the lake should be limed to pH> 6.0, thereby increasing the water quality at the outlet and downstream of the suggested lime dosing plant at the conjunction with Fifteen Mile Steam to pH> 5.5. To achieve pH> 6.0 until reliming the Ca-increase after liming should be 5.0 mg Ca L^{-1} as dissolved Ca. Based on this increase in Ca, dilution according to the retention time, and

long-term dissolution of sedimented limestone material the lake should be limed with 220 metric tonnes once a year.

Lime dosing in Seven Mile Stream.
The lime dosing plant should be upstream Lake Mulgrave (Purcell Pond). Alternative dosing further upstream (e.g. upstream Como Lake) would decrease the upstream/downstream dosing plant catchment-ratio to 0.33, which is close to non-acceptable. The site was visited as part of the inspection in June 2001, and is suited for liming. The liming details are given in **Table 3**. A total of about 210 tonnes yr^{-1} is required.

Lime dosing in Twelve Mile Stream.
The lime dosing plant should be downstream of Currys Stillwater (downstream of Union Dam Flowage). Water from Ten Mile Stream will thus be limed also. Alternatives further upstream, e.g. at Creelmans Crossing in Ten Mile Stream, would probably be in addition due to the relatively small catchment (61 km^2) and the necessity of having a dosing plant for the lower regions of Twelve Mile Stream. The site was visited as part of the inspection in June 2001, and is suited for liming. The liming details are given in **Table 3**. A total of about 360 tonnes yr^{-1} is required.

Lime dosing in Fifteen Mile Stream.
The lime dosing plant should be below the junction with Seloam Lake Brook. An alternative downstream of Anti Dam Flowage would be further downstream than necessary. It would also be difficult due to limited access to a possible dosing site at the outlet of the dam. The suggested site was visited as part of the inspection in June 2001, and is well suited for liming. The liming details are given in **Table 3**. This dosing plant will be suited for liming of the runoff from local catchments along Marshall Flowage and down to the sea. A total of about 340 tonnes yr^{-1} is required.

Liming of Grant River Catchment
Suggested for catchment liming due to limited access, acidity, and confluence with the main river at an area accessible for salmon. A limedose of 2 tonnes ha^{-1} with coarse-grained dolomite spread by helicopter will probably deacidify the whole catchment for decades. Total dosage is 5340 tonnes.

Table 3. Details for lake liming, lime dosing plants and terrestrial liming in East River, Sheet Harbour. Dosing sites are given in text. Actual doses for streams are calculated according to the catchment-ratio upstream/downstream of the dosing plant.

Locality	**Catchment[1], km^2**	**Total amount tonnes yr^{-1}**	**Dose at site, g m^{-3}**	**Comments**
Governor Lake	55	352	4.0	
Seloam Lake	40	220	5.0	
Seven Mile	91	208	3.2	No upstream liming
Twelve Mile	158	363	2.0	Governor Lake is limed; effect for 27.4 km^2 times 2.
Fifteen Mile	206	338	2.1	Seloam Lake is limed; effect for 20.0 km^2 times 2. Dose also for rest-catchment of Marshall Flowage to outlet.
Grant River	27			Terrestrial liming; 5340 tonnes
Total	577			

[1] Lake catchments multiplied by 2 are subtracted from their corresponding stream catchments.

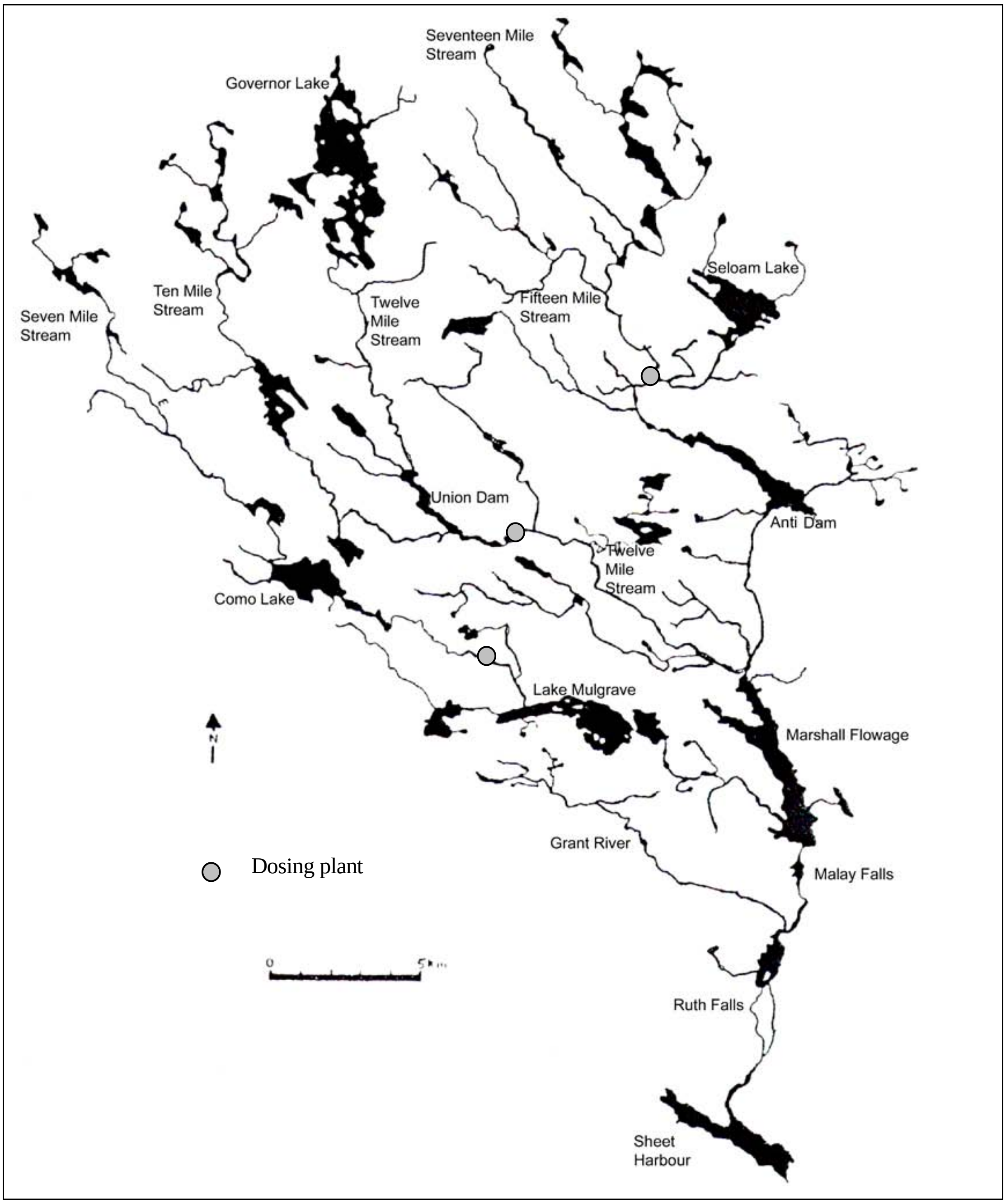

Figure 6. Liming strategy for East River, Sheet Harbour.

5.3 West River, Sheet Harbour

5.3.1 Possibilities and limitations

This river, as opposed to East River, is not regulated for hydroelectric power production, but is also characterised by a very low population density and lack of electricity in large parts. Many of the roads are seasonal and access may be limited. The river system is not as widely divided as East River, but Killag River is an important tributary, Lake Alma in the western branch is suited for liming.

West River is suited for liming. Liming of Lake Alma and lime dosing in the main river and in Killag River is recommended. Lakes in a smaller catchment in the lowermost part of the river system (Rocky Lake and others) may also be limed.

River lime dosing will be the dominating liming technique. Electric power is non-existant at the dosing sites and there may be limitations for access by trucks during the winter period. A successful liming project will probably be dependent on extra snow ploughing and one or several service people.

5.3.2 Recommended strategy

The suggested liming sites are shown in **Figure 7**.

Liming of Lake Alma.
Lake Alma has a water retention time of 0.6 yrs and is therefore suited for lake liming. pH was approximately 5.0 and the lake should be limed to pH> 6.0, thereby increasing the water quality at the outlet and downstream of the main river to pH> 5.5. To achieve pH> 6.0 until reliming the Ca-increase after liming should be 3.5 mg Ca L^{-1} as dissolved Ca. Based on this increase in Ca, dilution according to the retention time, and long-term dissolution of sedimented limestone material the lake should be limed with 220 metric tonnes once a year.

Liming of Rocky Lake and others.
These lakes have unknown water retention times. Liming may be done with five times the dose needed for the lakes themselves, but the duration is uncertain. A toal catchment of about 30 km^2 and a pH increase from 5.0 to 5.5 indicates a liming need of 50 metric tonnes yr^{-1}.

Lime dosing in Killag River.
The lime dosing plant should be downstream of Cameron Flowage. Alternatives further downstream would increase the upstream/downstream dosing plant catchment-ratio to above 0.50, but this is not necessary, and it is suggested to neutralise more of the river upstream rather than having the dosing plant further downstream. The site was visited as part of the inspection in June 2001, and is suited for liming. The liming details are given in **Table 4**. A total of about 100 tonnes yr^{-1} is required.

Lime dosing in the main river.
The lime dosing plant should be downstream of River Lake. Alternatives further upstream were not considered. The site allows for dosing for the rest of the catchment in West River (total minus Killag and Little River). It was visited as part of the inspection in June 2001, and is suited for liming. The liming details are given in **Table 4**. A total of about 220 tonnes yr^{-1} is required.

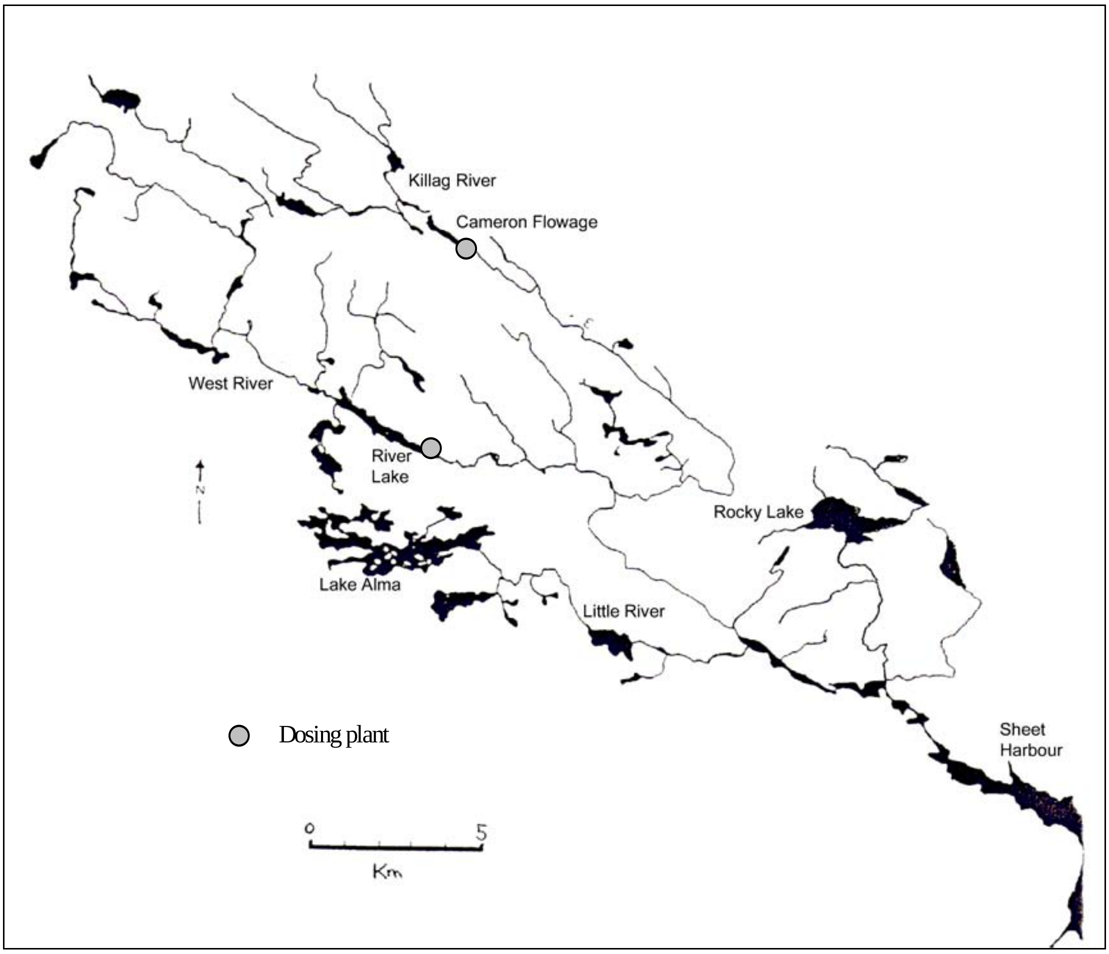

Figure 7. Liming strategy for West River, Sheet Harbour.

Table 4. Details for lake liming, and lime dosing plants in West River, Sheet Harbour. Dosing sites are given in text. Actual doses for streams are calculated according to the catchment-ratio upstream/downstream of the dosing plant.

Locality	**Catchment[1], km^2**	**Total amount tonnes yr^{-1}**	**Dose at site, g m^{-3}**	**Comments**
Alma Lake	36	220	3.5	
Rocky Lake and others	30	50	-	Based on uncertain figures
Killag River	63.4	105	2.7	No upstream liming
West River	133	220	2.2	Includes rest of West River
Total	262	595		

[1] Lake catchments multiplied by 2 are subtracted from their corresponding stream catchments.

5.4 LaHave River

5.4.1 Possibilities and limitations

This river is acidified in the western part, whereas the upper reaches and the eastern parts seem to have water qualities acceptable for Atlantic salmon. The upper western part (the Big LaHave Lake area) is characterised by very low population density and lack of electricity in large parts. Some of the roads are seasonal and access may be limited. The river system in this area consists mainly of Big LaHave Lake and West River in north and the slightly more populated area around Seven Mile Lake and West LaHave River in south.

These river systems are suited for liming. Liming of Big LaHave Lake, lime dosing plants in West River and West LaHave River, and terrestrial liming of the extremely acid catchment of Little River (south of Big LaHave Lake) is recommended.

River lime dosing will thus be the dominating liming technique. Electric power does not exist at the dosing site of West River but is available at the site in West LaHave River. Access by trucks may be limited at the first site during the winter period. A successful liming project may therefore be dependent on extra snow ploughing and one or several service people.

Sherbrooke Lake may be considered for liming. pH is about 5.5 and the water chemistry may represent a stressor for the trout population. However, this is not yet clarified, and the lake is not included in this liming plan.

5.4.2 Recommended strategy

The suggested liming sites are shown in **Figure 8**.

Liming of Big LaHave Lake.
Big LaHave Lake has a water retention time of 0.7 yrs and is therefore well suited for lake liming. pH was approximately 5.0 and the lake should be limed to pH> 6.0, thereby increasing the water quality at the outlet and downstream of the suggested lime dosing plant in West River to pH> 5.5. To achieve pH> 6.0 until reliming the Ca-increase after liming should be 2.8 mg Ca L^{-1} as dissolved Ca. Based on this increase in Ca, dilution according to the retention time and long-term dissolution of sedimented limestone material the lake should be limed with 270 metric tonnes once a year.

Liming of Little River Catchment.
Suggested for catchment liming due to extreme acidity, lost brown trout population and limited access. A limedose of 2 tonnes ha^{-1} with coarse-grained dolomite will probably deacidify the whole catchment for decades. Total dosage is 3400 tonnes.

Lime dosing in West River.
The lime dosing plant should be at Mill Pond by Simpsons Corner. Alternatives further upstream are hardly necessary to improve the water quality of these sections due to liming of Big LaHave Lake and Little River. The site was visited as part of the inspection in June 2001, and is suited for liming. The liming details are given in **Table 4**. A total of about 60 tonnes yr^{-1} is required. The dose is so low that 90% dissolution is anticipated.

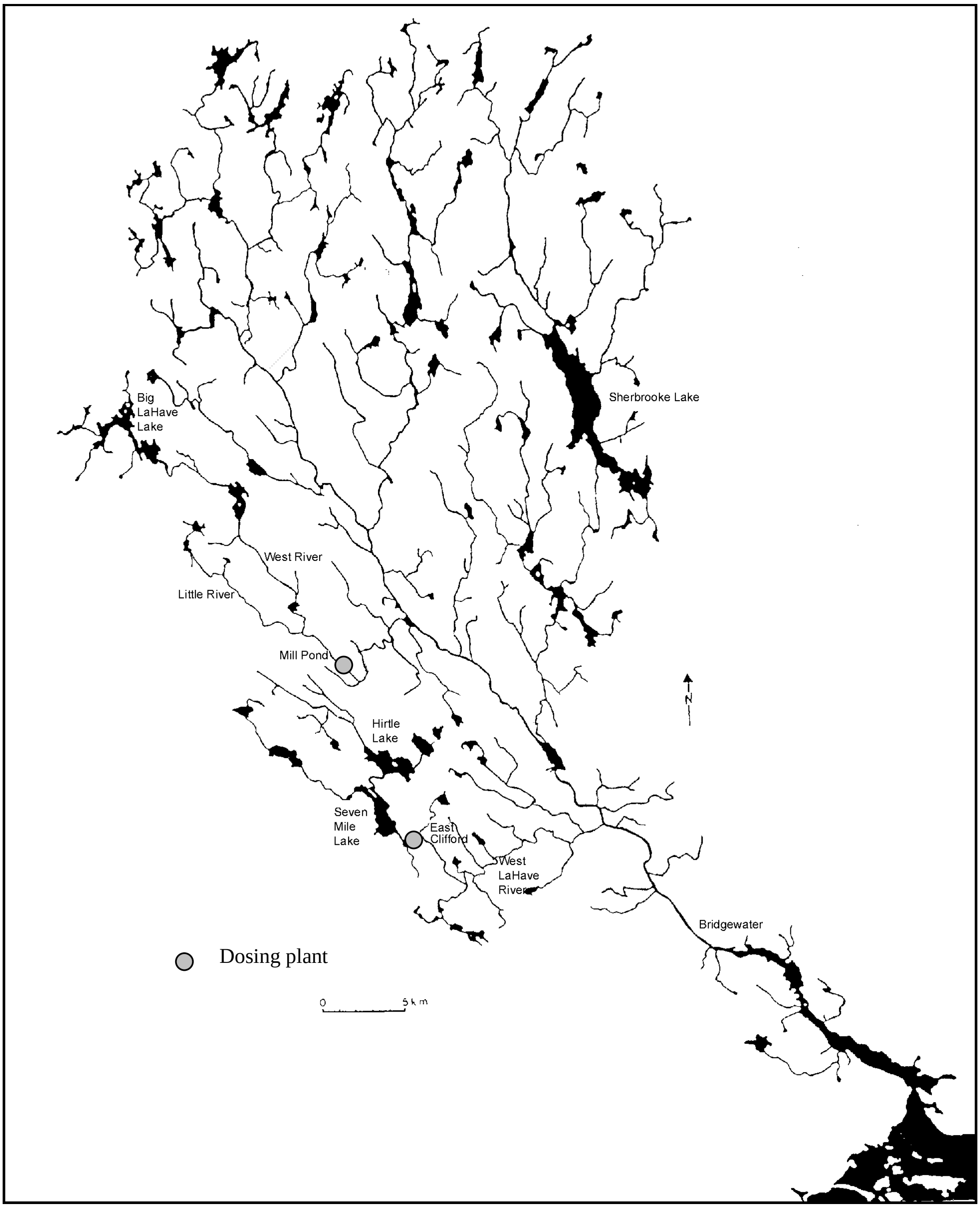

Figure 8. Liming strategy for LaHave River.

<u>Lime dosing in West LaHave River.</u>
This tributary will probably not contribute with unacceptable acidity to La Have River according to data from Lacroix, because pH is by and large above target levels of 5.5 at the confluence with the main river. If otherwise is chosen a lime dosing plant should be at East Clifford downstream of Seven Mile Lake. Alternatives further downstream (outlet of Fire Brook by Bakers Settlement or Hurtles Falls) are un-necessary. Lake liming upstream could be considered to improve water quality further upstream, but Seven Mile Lake has a retention time of only 0.2 years, which is too short for being suited for lake liming. This is also the case for Hirtle Lake (0.3 years). The dosing site at East Clifford was visited as part of the inspection in June 2001, and is suited for liming. The liming details are given in **Table 4**. A total of about 250 tonnes yr^{-1} is required for the whole catchment to raise pH by 0.5 unit.

Table 5. Details for lake liming, lime dosing plants and catchment liming in LaHave River. Dosing sites are given in text. Actual doses for streams are calculated according to the catchment-ratio upstream/downstream of the dosing plant.

Locality	**Catchment[1], km^2**	**Total amount tonnes yr^{-1}**	**Dose at site, g m^{-3}**	**Comments**
Big LaHave Lake	80	270		
Little River	17			Terrestrial liming; 3400 tonnes
West River	66	60	0.6	Big LaHave Lake and Little River upstream is limed
West LaHave River[1]	208	245	2.7	
Total	371			

[1] Lake catchments multiplied by 2 are subtracted from their corresponding stream catchments.

[2] pH of West La Have River is probably above target pH of 5.5.

5.5 Medway River

5.5.1 Possibilities and limitations

This river is characterized by being relatively long and more narrow than the other river systems. It also is more acidified than the other three rivers. The river is regulated for hydroelectric power production, does not have as low a population density as the others but lacks electricity in the upper parts. Some of the roads are seasonal and access may be limited, but intensive forestry may ensure acceptable access.

The river system is divided into two main parts in the upper half of the catchment. Alma Lake is headwater lake of the main river, and the Pleasant River system runs into the large Molega Lake before it joins with the main river system just upstream of Ponhook Lake. In between these rivers is the Tupper Lake system.

Few lakes have long retention time, and the large lakes in the middle of the catchment (Molega and Ponhook) have a large catchment upstream which make them less suitable for lake liming. Outlet and inlet of Lake Molega are so close, however, that lake liming may create good water quality for a large part of the lake in spite of the short theoretical retention time of the lake.

A fishway for upwards migrating salmon does exist at the outlet of McGowan Lake. Full benefit of this construction may be reached by liming of the river upstream the lake, as suggested above.

Medway River is suited for liming. Liming of Alma Lake, Molega Lake, lime dosing plants in Pleasant River, and at three sites in the main river is recommended. We also recommend liming of the smaller tributary from Christopher Lakes (Cameron Brook). The uppermost dosing site in the main river is suggested downstream of the conjunction of west and east branch of Medway, the next at the outlet of Eel Lake upstream of South Brookfield, and the third at the outlet of Ponhook Lake.

Tupper Lake and Round Lake may be limed but the retention time is probably too short to give acceptable water quality for a whole year. Liming of these lakes is probably not neccessary for the salmon population of Medway as long as a lime dosing system is operated in the main river. Harmony Lake southwest of McGowan Lake is also fit for lake liming, but the water quality there is acceptable and the lime dosing plant in the main river will improve the water quality further downstream.

Lakes north of Highway 103 northeast of Liverpool are very acid and should also be limed.

Lime dosing will thus be the dominating liming technique in Medway River. Power exists at all sites and access is probably good at all times of the year. Successful dosing may also be ensured by co-operation with local people in this somewhat more densely populated area.

5.5.2 Recommended strategy

The suggested liming sites are shown in **Figure 9**.

Liming of Alma Lake.
Maximum depth of Alma Lake was unknown, and has been arbitrarily sat at 15 m. Based on surface area and the hypsographic curve technique referred to under Material and Methods the lake volume was estimated at 13.6 mill. m^3. Together with runoff data, this gives a water retention time of 0.2 yrs. The lake is therefore not suited for lake liming if the aim is to maintain pH> 6.0 for one year. However, if the lake is limed in late autumn (November) and is ice-covered during wintertime prolonged duration (longer than indicated by the retention time) of the liming-effect may be expected. The overall aim of increasing the survival and reproduction of Atlantic salmon may justify a water quality improvement restricted to the period November-May. Salmon smolts are especially sensitive and will probably profit by this strategy.

Liming may be done by increasing the Ca-concentration by 5.0 mg Ca L^{-1} as dissolved Ca. Based on this increase the lake should be limed with 270 metric tonnes once a year.

Liming of Molega Lake.
Molega Lake has a water retention time of 0.6 yrs and is therefore suited for lake liming. Although the maximum depth is 26 m the mean depth is only 4.6 m. Sinking depth for limestone powder is therefore not as large as indicated by the maximum depth. pH at the outlet was 5.0-5.5 in periods and the lake should be limed to pH> 6.0, thereby increasing the water quality at the outlet to target pH for salmon. To achieve pH> 6.0 until reliming the Ca-increase after liming should be 2.0 mg Ca L^{-1} as dissolved Ca taking into account liming of Pleasant River upstream. Based on this increase in Ca dilution according to the retention time and long-term dissolution of sedimented limestone material the lake should be limed with 795 metric tonnes once a year.

Liming of lakes along Highway 103.
Lakes along Highway 103 and to the north-west have unknown volumes and water retention times. The total catchment of Salters Brook and Oakes Mill Brook is 142 km^2. Liming may be done by distributing the estimated amount of about 180 metric tonnes yr^{-1} on the lakes. However, lime dosing of Salters Brook by this amount would be a better solution but access is very limited.

Lime dosing of Pleasant River.
This tributary is acid, and pH is below 5.0 most of the year. The lime dosing plant should be at the bridge 800 m upstream of Highway 208 by Pleasant River. Alternative sites were not considered. Liming here should deacidify runoff also from Shingle lake catchment, which in practise will mean the whole tributary down to Molega Lake. The dosing site was visited as part of the inspection in June 2001, and is suited for liming. Liming details are given in **Table 6**. A total of about 240 tonnes yr^{-1} is required.

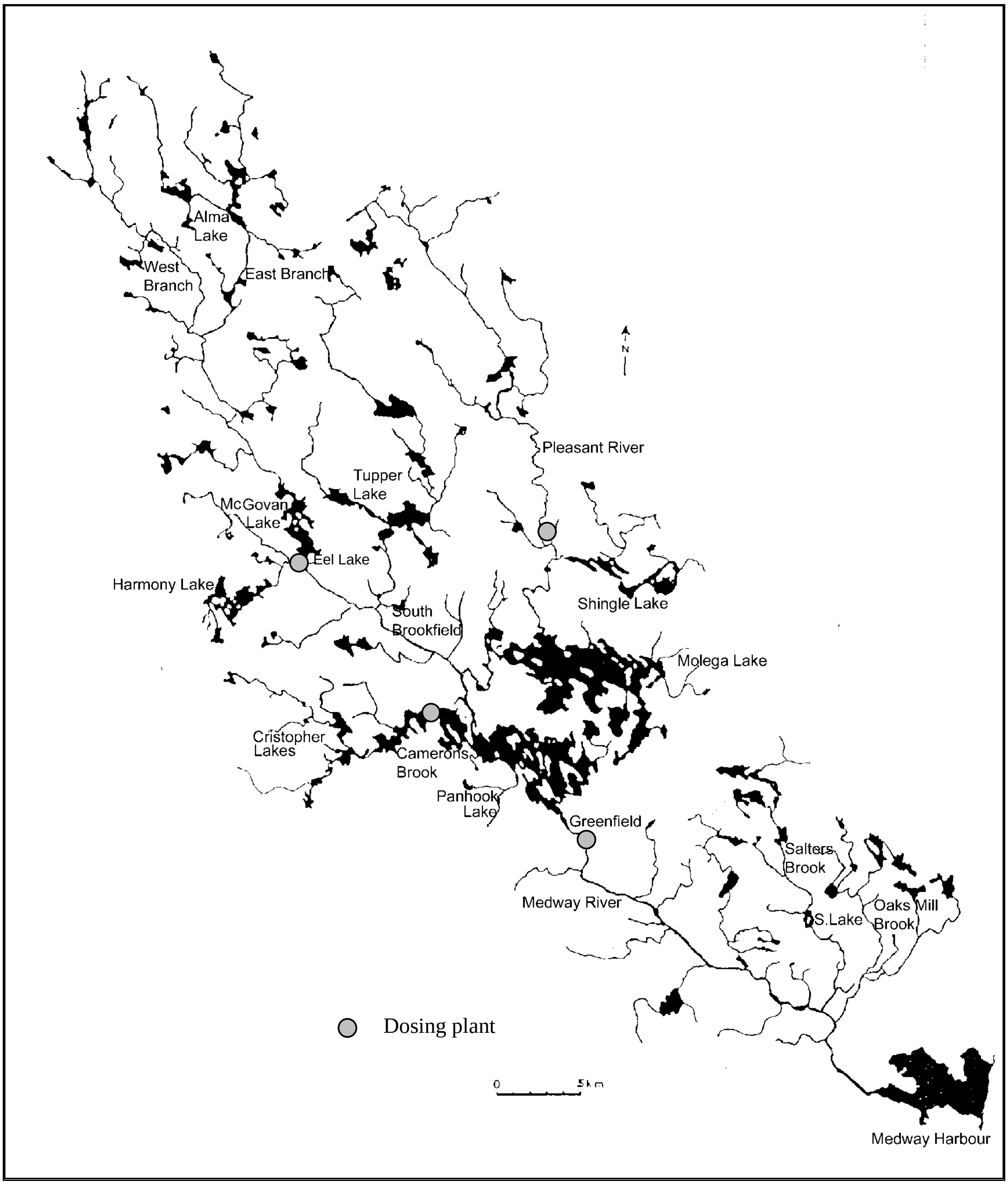

Figure 9. Liming strategy for Medway River.

<u>Lime dosing of Medway River below junction of East and West Branch.</u>

The lime dosing plant should be at the bridge (house with old aggregate) downstream of the junction of east and west branches in the upper part (upstream of McGowan Lake). Alternatives further upstream were not considered, but the bridge immediately upstream of McGowan Lake is also suited for lime dosing. Lake liming of Alma Lake upstream is suggested, but a retention time of only 0.2 years does not allow for a full inclusion in the liming strategy. The Alma catchment is therefore not subtracted from the total catchment for the lime dosing. Harmony Lake has acceptable water quality, and the catchment of 25 km^2 is therefore subtracted. The dosing site was visited as part of the inspection in June 2001, and is suited for liming. The liming details are given in **Table 6**. A total of about 400 tonnes yr^{-1} is required for acceptable water quality downstream to Eel Lake.

Lime dosing of Medway River at Eel Lake (Alt. 1).
The lime dosing plant should be at the outlet of Eel Lake downstream of McGowan Lake. The dosing plant should be controlled by pH upstream together with flow and should deacidify the river all the way down to the outlet of Ponhook Lake (Greenfield). An alternative to this strategy (Eel Lake-2) is given below. The limestone powder amount was estimated by excluding the catchments upstream of Eel Lake, Molega Lake, and Camerons Brook. The site was visited as part of the inspection in June 2001, and is suited for liming. The liming details are given in **Table 6**. A total of about 300 tonnes yr^{-1} is required.

Lime dosing of Medway River at Greenfield at the outlet of Ponhook Lake.
This dosing plant should only be considered together with Eel Lake, Alternative 1. The lime dosing plant should be controlled by the pH upstream together with flow and should be placed at the outlet of Ponhooke Lake at the large bridge by Greenfield. Alternatives further downstream were considered but abandoned due to important spawning sites immediately downstream of the bridge. The dosing site was visited as part of the inspection in June 2001, and is suited for liming. The liming details are given in **Table 6**. A total of about 365 tonnes yr^{-1} is required.

Lime dosing of Medway River at Eel Lake (Alt. 2).
In this alternative the lime dosing plant will deacidify the river all the way down to the sea. The limestone powder amount is estimated by excluding the catchments upstream of Eel Lake, Molega Lake, and Camerons Brook. The liming details are given in **Table 6**. A total of about 750 tonnes yr^{-1} is required, which is more than Alternative 1 due to higher dose and anticipated lower dissolution.

This alternative is presented to show that liming with only one dosing plant from Eel Lake to the sea is possible when it comes to dose size and dissolution. However, a dosing site upstream Ponhook Lake is a disadvantage for good control of the water quality downstream of the lake. If, of some reason, the water quality of Ponhook Lake becomes unacceptable, it may take too long to improve it by increasing doses at Eel Lake.

Lime dosing of Camerons Brook.
The lime dosing plant should be at the bridge in the Provincial Park upstream of the Highway 8 crossing (not at the road bridge). Alternative dosing sites were not considered. Runoff from this catchment of 101 km^2 may also be deacidified by including it in the estimates for the Eel Lake dosing plant. This would increase the catchment ratio, but only to 0.44, which is acceptable. Lake liming upstream could be considered, but the retention times of the lakes may be too short. No data exist, however to consider this more closely. The dosing site was visited as part of the inspection in June 2001, and is suited for liming. The liming details are given in **Table 6**. A total of about 128 tonnes yr^{-1} is required.

Table 6. Details for lake liming, lime dosing plants and catchment liming in Medway River. Dosing sites are given in text. Actual doses for streams are calculated according to the catchment-ratio upstream/downstream of the dosing plant. Total amounts are not included in the table due to the alternative strategies.

Locality	**Catchment[1], km^2**	**Total amount tonnes yr^{-1}**	**Dose at site, g m^{-3}**	**Comments**
Alma Lake	95.5	270		
Molega Lake	197[2]	795		Amount not included in other estimates
Lakes along Highway 103	142	180		Amount not included in other estimates
Pleasant River	191	240	1.8	Shingle Lake catchment included
Camerons Brook	101	128	1.3	may be omitted and included in Eel Lake dosing
Medway River to Eel Lake outlet	321	405	2.3	Harmony Lake catchment not included; Alma Lake included
Medway River; Eel Lake to Greenfield	311	305	0.9	This is Eel Lake-1; together with next (Greenfield to outlet)
Medway River; Greenfield to outlet	372	365	0.4	Should be combined with previous (part of Eel Lake-1)
Medway River; Eel Lake to outlet	683	755	2.3	This is Eel Lake-2; alternative to two previous

[1] Lake catchments multiplied by 2 are subtracted from their corresponding stream catchments.

[2] Effective catchment area is 339-142=197 km^2 due to liming of Pleasant River.

5.6 General recommendations

A successful mitigation program is dependent on co-operation between federal and provincial authorities, liming and power production industry, research institutions, fishing organisations, local authorities, land owners and the local public.

The Scandinavian model with a parallel research and monitoring program may ensure liming according to the best available knowledge. Success may also be dependent on a certain amount of central instructions regarding conditions for getting funding, principles for liming, and documentation of liming effects. Monitoring of water quality in reference rivers should be part of a research program. Results from this kind of monitoring will tell if and how much the general acidification situation changes in the future. A long-term liming plan may thereby also be made, especially if based on critical load (CL) exceedances. CL calculations have been used in this way in Norway (Hindar et al. 1998).

A liming program should probably start up with a few full-scale project to get training experience with different liming techniques. A co-operation between Scandinavian and Canadian liming industry may reduce the time needed to gain experience. Most of the techniques and experiences already exist and there should be no reason for doing things over again. However, full advantage of the potential for cost reductions may not be reached before a market is established for sale of limestone products and lime dosing plants.

Operational liming is costly but may give many positive values in return. Research in Scandinavia has revealed both direct income due to sale of fishing licenses, value of fish, increased demand and thereby value of lodging and due to increased retail trade. Indirect income for the society may be connected to increased recreational value of the area, and the general value in many peoples opinion of an undisturbed nature.

5.7 Monitoring program

This work has shown that there is a lack of comprehensive chemistry data for several localities. More precise estimates of the acidity situation and liming needs require additional data. This is especially true for tributaries, and thereby the basis for strategic liming of those. A monitoring programme for water chemistry, which includes tributaries in the four river systems, would certainly improve the situation.

Measures to improve water quality should be accompanied by a chemical and biological monitoring program in aquatic and terrestrial (if catchment liming) ecosystems. In this way large-scale liming in Nova Scotia may be evaluated on basis of costs, effects on fish resources, genetic values and recreation, and undesired effects may be documented.

Most important is a chemical monitoring program. This is due to the close relation between lime doses and chemical effects, and the relatively close relationship between water chemistry and biological response. Monitoring should be tailored according to liming techniques and characteristics of each limed locality. In general, a chemical monitoring program should be designed to reveal if the chosen liming strategy is acceptable, if the liming operation is run satisfactory, and if acceptable water quality is produced at target sites. In the case of the Nova Scotian rivers target sites will mean Atlantic salmon producing sections. However, liming relatively far from such areas will improve water quality also in streams and lakes without salmon. Other biological targets may be defined or one may be restricted to the more technical strategic value of the site.

As liming will be initiated on the basis of the value represented by self-reproducing Atlantic salmon, a monitoring program should also be established to document effects on salmon reproduction. Electrofishing to get data on reproduction success and fishing traps for sampling of smolt for quality control will be central. Counting of spawners migrating up-stream should also be accomplished if possible.

Together with increased salmon production, increased biological diversity should be a fundamental aim for liming operations. Monitoring of biological diversity is demanding, but may be done by looking at indicator organisms. The salmon itself will be a good indicator due to its sensitivity, especially represented by the salmon smolt life stage. However, invertebrate studies and indexes based on the species composition will give a broader documentation of the effects.

Terrestrial ecosystems may be changed after liming of terrestrial compartments. Important monitoring subjects are water chemistry of streams, terrestrial microflora and higher vegetation. Sphagnum mosses, liverworts, and lichens are known to be especially vulnerable after liming. Acidophilic species may be reduced.

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Appendix A. River and Lake Characteristics

(data received from the Atlantic Salmon Federation)

Some of the catchment areas in the following tables have been recalculated by the author and are given in the main text of the report.

Catchment Areas of Four Rivers and their Tributaries, Nova Scotia

		Latitude		Longitude		
River system	Site	deg	min	deg	min	Catchment Area (hectares)
East River, Sheet Harbour	Fifteen Mile Stream below junction with Seloam Lake Brook	45	5	62	2	13022,5
East River, Sheet Harbour	Ten Mile Stream at Creelmans Crossing	45	7	62	41	6063,75
East River, Sheet Harbour	Seven Mile Stream at bridge above Como Lake	62	42	45	6	2945
East River, Sheet Harbour	Twelve Mile Stream at road below Currys Deadwater	45	6	62	37	14433,75
East River, Sheet Harbour	Seven Mile Stream at bridge above Lake Mulgrave	45	3	62	36	2006,75
East River, Sheet Harbour	Grant River					2674
East River, Sheet Harbour	Whole catchment					44122
West River, Sheet Harbour	Killag River	45	0	62	39	6367
West River, Sheet Harbour	Litle River	44	57	62	37	3544
West River, Sheet Harbour	Killag River at Bridge	44	59	62	37	5147
West River, Sheet Harbour	Killag River at Beaver Dam Road	45	4	62	42	3561
West River, Sheet Harbour	Outlet of River Lake	43	1	62	43	8105
La Have	Whole catchment above Bridgewater					160204
La Have	West La Have River, Whole catchment	44	33	64	45	16262,5
La Have	West La have at Highway 208	44	32	64	47	11055
La Have	West Lake Outlet	44	33	64	49	8437,5
La Have	Little River at bridge	44	33	64	50	1712,5
La Have	Outlet of Big La Have Lake	44	38	64	56	3947,5
La Have	Rhyno Lake Outlet at East Clifford	44	26	64	44	10215
La Have	Catchment above New Germany	44	33	64	43	58441
Medway	Pleasant River at bridge 800 m upstream of Highway 208	44	26	64	53	14217
Medway	Below junction of East and West Branches of Medway River	44	32	65	8	18822
Medway	Eel Lake Outlet downstream of McGowan Lake	44	25	65	3	34549
Medway	Between First Christopher and Cameron lakes	44	20	64	57	10068
Medway	Medway River at South Brookfield	44	22	64	58	53083
Medway	Medway, total catchment					146752
Medway	Salters Brook and Oakes Mill Brook	44	11	64	40	14226

Upstream Catchment Areas, Surface Areas, Lake Volumes and Maximum Depths of some Nova Scotia Lakes

System	Lakes	Latitude		Longitude					
	Site	deg	min	deg	min	Catchment Area	Surface Area	Volume	Max depth
						ha	ha	m^3	m
East River, Sheet Harbour	Seloam Lake	45	10	62	30	2000	291,4	9 350 000	12,2
East River, Sheet Harbour	Governor Lake (including Otter Lake)	45	13	62	41	2744	651,5	19 103 000	12,8
West River, Sheet Harbour	Alma Lake	44	59	62	45	1783	440,0	13 491 000	19,0
La Have	Sherbrooke Lake	44	40	64	36	30190	1660,0	136 288 000	24,4
La Have	Hirtle Lake	44	28	64	45	5975	330,0	15 246 000	14
La Have	Seven Mile lake	44	27	64	46	9580	291,0	16 811 000	18
La Have	Big La Have Lake	44	38	64	56	3948	417,0	unknown	unknown
Medway	Shingle Lake	44	25	64	88	4907	461,0	9 281 000	14
Medway	Molega Lake	44	22	64	51	33933	2168,0	100 478 000	26
Medway	Ponhook Lake	44	16	64	50	109613	1596,0	unknown	unknown
Medway	Alma Lake	44	37	65	7	Catchment without Mitchell Brook=8284 ha. With Mitchell bk = 9550 ha	271,0	unknown	unknown
Medway	Harmony Lake	44	24	65	6	2476	354,0	16 289 000	11
Medway	Hell Lake	44	15	64	36	423	87,0	unknown	unknown
Medway	Island Lake	44	15	64	35	503	102,0	unknown	unknown

Mean monthly and annual discharges (m3/s), Nova Scotia Rivers

	La Have R. (West Northfield)	**Medway R. (Charleston)**	**Liscomb R. (Liscomb Mills)**	**Musquodoboit R. (Crawford Falls)**
Latitude (North)	44, 26, 48	44, 10, 24	45, 00, 54	44, 52, 18
Longitude (West)	64, 35, 30	64, 39, 36	62, 08, 45	63, 13, 18
Drainage area, km2	1250	1390	389	550
Years of record	1915-1990	1915-1990	1962-1988	1915-1988
Month				
Jan	46,8	57,9	18,1	25,5
Feb	38,9	51,5	14,7	19,7
Mar	52,4	62,1	20,5	28,3
Apr	73,4	81,3	29,9	39,2
May	38,9	50,3	19,4	22,9
Jun	20,9	28,9	9,5	11,8
Jul	11,7	16,9	7,5	7,2
Aug	9,3	12,0	8,1	8,6
Sep	9,2	11,6	6,6	8,0
Oct	20,3	20,7	13,1	15,1
Nov	42,0	43,5	21,8	26,7
Dec	50,6	59,9	22,5	28,2
Annual mean	34,4	41,3	15,8	20,1

Appendix B. Dose calculations

Dose calculations were based on theoretically constructed titration curves according to TOC-level, see the figure below. The basis for the curves is contribution to $CaCO_3$ –consumption from H^+, alkalinity and organic acids at different pH-steps starting at pH 4.5. As this calculation assumes a 100% dissolved titrant, reduced dissolution, as is experienced in liming of lakes and rivers, has to be corrected for.

Actual dissolution in lakes is dependent mainly on lake depth and pH, and is documented in the literature (Sverdrup 1985). Dissolution in rivers is also dependent on turbulence, and may thus vary to a great extent along the river and during a year due to changing gradients along the river and seasonal variations in runoff, respectively. Documentation on how dissolution in rivers varies is almost nonexistant.

In addition to the instantaneously dissolved limestone powder (dissolution as the powder sinks to the lake or river bottom), long-term dissolution has to be considered as this contributes to the total dissolution until reliming or to the annual dissolution in rivers. Data for dissolution, as given in the text, is based on experience and should be regarded as guiding numbers.

The factors contributing to the uncertainties of dose calculations will also result in relatively large variations in the actual amount of limestone powder used in each river on an annual basis.