REVIEW OF FISHERIES RESEARCH BRANCH, SCOTIA-FUNDY REGION, ACID RAIN STUDIES

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INTRODUCTION

The acid rain program for the Fisheries Research Branch, Scotia-Fundy Region, may be separated into four components: Surveys and monitoring, "intensive" ecological studies, laboratory studies, and mitigation. We have combined surveys and monitoring together, because operationally and philosophically they are very similar. Their function is to give us a grasp of the status quo of fishery status - water chemistry, etc., in a particular geographic region - without revealing very much about what is happening in a mechanistic sense. They allow us to sit back and look at trends over broad geographical regions or fairly long temporal periods. That is not to say that these studies may not provide some insight as to mechanisms, but, it seems to us, that is not the primary objective. The so-called "intensive" ecological studies, on the other hand, may be experimental and manipulative. They seek to provide some real understanding of how acidification affects organisms and populations in their natural habitat. The laboratory studies seek further refinement of mechanisms at the organism or cellular level under more controlled conditions. They may do no more than provide estimates of lethal thresholds, or they may provide relatively sophisticated answers as to what is happening at the cellular or molecular level. The four components, of course, are not discrete, but form a continuum with areas of overlap. Much of the "intensive" ecological research, for example, provides excellent baseline data for a monitoring program. Streamside physiological studies may provide a link with laboratory experiments. The types of mitigation measures to be implemented are, in turn, dependent on the results of the other three components and seek to restore, in part or wholly, previous conditions - chemically and biologically.

The above mentioned research studies, mitigation, monitoring and surveys have been undertaken by the Fisheries and Environmental Sciences Division in St. Andrews, N.B., and Halifax, N.S., and the Freshwater and Anadromous Division in Halifax. Most laboratory research is based in St. Andrews with the exception of the work on adult maturation processes which is carried out at the Halifax Fisheries Research Laboratory. A list of Fisheries Research Branch acid rain publications is appended to this report (Appendix I).

All of the studies conducted by the Scotia-Fundy Region are directly related to the Departmental program goal "to protect freshwater and anadromous fisheries resources threatened by acid precipitation and related pollutants". Also, all of the studies described here are related to objective 1 - namely to address "the production of significant scientific documentation on the effects of acid rain to fisheries".

MONITORINIG AND SURVEYS

I. Surveys: The National Inventory

The Maritime portion of the National Inventory of lakes (similar surveys were performed in Ontario, Quebec, and Newfoundland) (we use Maritime here because about 15 lakes were surveyed in the Gulf Region as well) probably provides the best overall picture of how headwater lake chemistry varies geographically within the Maritimes, combined with corresponding presence-absence information on some of the more important fish species (on a sportfishing basis).

The lake chemistry data from the 145 lakes (76 in N.S., 69 in N.B.) were sufficiently varied that one could get, for example, good response surfaces of total dissolved aluminum and iron concentrations as functions of lake pH and TOC. This is so because the distribution of TOC values for N.B. and N.S. lakes, surprisingly enough because the organic nature of Nova Scotian lakes have received much publicity, are fairly similar - but the Nova Scotian lakes are much more acidic. Obviously, TOC was not sufficient to adequately characterize the pH-organic acid relationships of the lake waters sampled, but it did seem adequate to examine the influence of dissolved organics on Al and Fe solubilization.

By analyzing Ca-Mg-alkalinity relationships[1], one can conclude that there seems to have been an alkalinity loss of 20-30 µeq/L from most Maritime lakes. However, considering some of the more recent ELA publications, perhaps these relationships should be used with caution. Interestingly, though, lakes from northern N.B. and Cape Breton do not, on the average, exhibit "alkalinity loss" as defined by the Henriksen model.

Perhaps the most interesting data provided was the presence-absence data for brook trout and yellow perch from the gill-netting studies. The data may be interpreted as suggesting that a competitive relationship exists between the two species in the region. As a result of acidification in N.S. lakes, perch have become increasingly frequent in the more acidic lakes and the less acid-tolerant brook trout less frequently encountered.

The zooplankton data (analyzed and published by Dr. J. Carter) indicate that chemistry factors related to lake acidity were one of the major determinants of zooplankton species composition - other important factors were related to salinity and to amounts of dissolved organic carbon.

The analyses of heavy metal burdens in fish indicate that lake acidity is important in determining amounts of lead in fish from Maritime lakes. The relationship was most striking for yellow perch, as this species was most frequently sampled from the more acidic lakes, but it can be seen for brook trout and white suckers as well. The body burdens of other metals analyzed (Cd, Cu, Zn, Hg) seemed to be related more to geographical influences than to major ion chemistry of lake waters.

The survey also indicated that the presence of molluscs (Gastropoda and Pelecypoda) were restricted by lake pH - as has been shown by surveys conducted in other acid-stressed regions. A much smaller local survey of lotic invertebrates from 20 streams in N.B. and N.S. indicated that several mayfly species (Baetis and some Ephemerella species, particularly) had probably had their geographic distribution reduced by low stream pH.

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[1]Henriksen, A. 1982. Susceptibility of surface waters to acidification, p. 103-121. In Acid Rain/Fisheries, Proc. Int. Symp. on Acidic Rain and Fishery Impacts on NE N.A. Am. Fish. Soc.

The major emphasis on Maritime survey work this far has been on headwater lakes and Atlantic salmon stream populations in Nova Scotia. We know practically nothing on possible reductions in geographic distributions on non-salmonid stream fishes (e.g., Cyprinidae) due to stream (and lake) pH. Given the priorities of Departmental research in Atlantic Canada, we probably never will. With certain qualifications, however, these surveys have provided some good baseline biological and chemical data from which to launch further monitoring programs.

II. Monitoring of Ten New Brunswick Lakes

We began monitoring 10 lakes in southern N.B. in 1978, intending to do the water chemistry every month from April to November, every five years, and survey the fish populatons every 10 years. Thus, we have water chemistry records for 1978 and 1983, and data on the fish populations for 1978 - due to be sampled again in 1988. The lakes vary widely in water chemistry with three of them having pH levels near 5.7 and near zero alkalinity, and one of them with a pH of 7.5 and 500 μeq/L alkalinity. All can be classified as "clear water" lakes. There was no evidence of any change in water chemistry from 1978 to 1983 that could not be related to differing precipitation patterns between the two years. In the future, we will probably enlarge the number of lakes in the network to 12 to include one in southern N.B. (sampled in the survey) near pH 5.0, and one organic lake in N.S. We may also include some work on fish populations in the cluster of Nova Scotian lakes that DOE plans to monitor. We understand DOE has not included N.B. in their monitoring network, relying on the St. Andrews Biological Station program to fill the gap.

The aim of the lake monitoring program is to be able to recognize significant acidification, if it occurs, and to monitor the health of fish populations - emphasizing brook trout which are present in 7 of the 10 lakes. We will be particularly interested in reproductive success.

The 5-yr sampling frequency has been criticized by those organizing the DOE monitoring network; however, as it stands, it is a program we feel we can maintain, considering funding uncertainties and manpower shortages. Other projects in the program, which we consider to have higher priority, more or less force us to do these lakes infrequently.

There are limnological records for two of the lakes, dating back to the late 1940's, when Morden Smith was doing limnological work in the area. These lakes are not the most "sensitive" in the suite - pH ca. 6.5 - and there is no indication of any pH change over 40 years, given uncertainties due to differing analytical methods between now and then. Two of the lakes have been cored and diatom analyses indicate that the pH has declined, 0.5-1.0 pH in some unbuffered N.B. lakes during the last 70 yr.

III. Support for Research Conducted at the Kejimkujik Calibrated Watershed Study

For the years 1981-1983, the DFO LRTAP program provided some financial assistance for work conducted at the Kejimkujik Calibrated Watershed study as part of the DOE LRTAP program. Studies which received DFO support included: analyses of fish sampled from the three lakes in the Watershed study, a histological study of gill tissues from white perch inhabiting waters of varying pH in the Park, and a study of zooplankton communities in the study lakes. The analyses of fish samples indicated that yellow perch in some of the Park lakes are growing more slowly than in those sampled from some of the N.B. lakes monitored. This may well be a density-dependent effect, rather than related to acid stress. White perch appeared to be much more short-lived in some of the acidic Park lakes (maximum age observed was 6 yr) as compared to some N.B. populations (up to 14-15 yr of age); although growth rates were greater for the Nova Scotian perch.

IV. Monitoring of Maritimes Surface Water Chemistry and Atlantic Salmon Populations

The principal objectives of this program are to determine to what extent waters in the Maritimes Region have been acidified by acid precipitation, what chemical mechanisms are involved, and to determine the nature of the response of surface water acidification on Atlantic salmon populations of Nova Scotian rivers.

1) Chemical monitoring: Alarmed by the declining pH's reported for eastern Canadian precipitation in the mid 1970's, the Habitat Protection Section began, in 1977, to examine surface water data in the Maritime Provinces for indication of acidification. A 1979 survey of 22 Nova Scotian lakes, which were first examined in 1955, showed that 16 of these lakes were still in a relatively undisturbed state except for atmospheric input and that all 16 had lower pH's.

During 1978-80, a more extensive survey of water chemistry in the Atlantic salmon rivers of the Maritimes area was conducted. This survey revealed that the only severely acidified area in the Maritimes was the Atlantic Upland area of Nova Scotia. This is an area of shallow soils and poor drainage, underlain by granites and metamorphic rocks lacking in basic minerals. The area contains 42 known Atlantic salmon rivers of which 13 were found to have mean annual pH's less than 4.7, 13 had pH's in the range 4.7-5.0, eight had pH 5.1-5.4 and eight were of pH greater than 5.4.

The next step was to examine the chemistry of these rivers in detail to see how such acidification had come about. During 1980-81, monthly samples were analysed from 23 rivers flowing through the Southern Upland (a geological area roughly south of a line drawn between Digby and Guysborough, Nova Scotia). A close correlation with geology was confirmed as was the relationship between pH and discharge. Minimal pH's typically occur in mid-winter and then rise gradually throughout spring and summer until the onset of autumn rains when pH falls dramatically. The range of seasonal variation is less than 1 pH unit.

We have never encountered any evidence in our monthly or daily data of significant episodic pH depressions such as have been reported elsewhere in North America and Scandanavia under snowmelt conditions. River pH's show an inverse correlation with flows, but very high flows do not induce proportionately low pH's. The pH depression during freshets (March and April) relates directly to spring precipitation.

Snowfall-melt water is always higher in pH than rainfall. This is due to the extremely low ionic concentrations occurring in snow, rather than the presence of any acid buffering capacity. The effect of a snowmelt in Nova

Scotia is typically to dilute acids present in the rain and surface waters, thus causing a slight rise in river pH's. In general, however, snowmelts are not major sources of runoff in the Southern Upland rivers, and most freshet flows are the result of direct runoff of rain. The pH of precipitation varies seasonally, being much lower in summer than in winter. The lowest pH precipitation is usually carried in winds from the southwest quadrant, which is the major prevailing wind direction in summer and also the direction of the major pollution sources in the eastern U.S.A. The highest pH's occur in precipitation from the northeast (i.e., from the North Atlantic and Newfoundland) which is our commonest wind direction for snow.

For five rivers, the monthly data collected in 1980-81 can be compared to similar monthly data collected in 1954-55. All five show a fall in pH over this 26-yr period. Unfortunately, two points in time are not adequate to prove a trend, and, for most sites, that is all that we have at present. By a fortunate coincidence, however, one site on the Medway River was also sampled monthly during the period 1965-78 by Environment Canada. When these data are combined with Habitat Protection data from 1979-84, they clearly show a declining pH trend in this river ($p < 0.01$).

In summary:

(1) Highly significant pH reductions were demonstrated in N.S. lakes and rivers relative to published chemical data from the 1950's. The pH declines are accompanied by declines in alkalinity and colour and increased concentrations of aluminum and sulphate.

(2) The acidification on Maritimes surface waters is closely correlated with soil and bedrock geology. Only drainages with non-alkaline rocks and shallow soils show severe acidification of the lakes and rivers.

2) Atlantic Salmon Field Studies: All 42 of the rivers flowing through the Southern Upland area of Nova Scotia have probably supported Atlantic salmon stocks. Nearly continuous salmon angling records are available from 1936 to the present for 27 of the Southern Upland rivers. Significant dam construction and/or removal and/or hatchery stocking have occurred on five of these rivers, but 22 of them remain in a state which is very similar to their condition as it was 48 yr ago.

For rivers presently of pH less than 4.7, the angling record ends in the 1970's and extensive electrofishing in these rivers has failed to discover any surviving juvenile salmon. We have concluded that for rivers at this pH level, the salmon runs are now extinct. This accounts for 13 rivers in the Southern Upland. For another 13 rivers in the pH range 4.7-5.0, the angling catch has declined to about 10% of levels prevalent during the 1936-53 period. Electrofishing data from these rivers usually indicate the presence of small populations of salmon juveniles, commonly in higher pH tributaries which function as natural refuges. The decline in salmon angling returns was simultaneous in the rivers of pH less than 4.7 and in the pH 4.7-5.0 rivers. Between 1950 and 1959, both of these lower pH river groupings suffered a 60% decline in angling success. The salmon stocks of the rivers in the pH less than 4.7 group have since disappeared, because of lower acid neutralization capacity in their catchment basins which has resulted in the present lethal levels of acidity.

The 16 rivers in pH categories 5.1-5.4 and greater than 5.4 show no sign, yet, of an impact of acidification on angling returns, though there is electroseining and toxicity evidence of acidification impacts occurring now and limiting juvenile salmon production in the lower pH tributaries (pH near 5.0) of some of these rivers.

The Atlantic salmon no longer have access to 13 rivers and if the acidification is permitted to proceed at the same rate as in the recent past, then we must expect to lose the salmon stocks from another 13 rivers for a total of 26 extinct stocks by about the year 2000. In addition, we can expect that one-half of the remaining rivers (the 8 now in pH range 5.1-5.4) will suffer stock reductions on the order of 90%.

Experience has shown that it is very hard to establish self-sustaining populations of salmon using parental fish which have been transplanted long distances between rivers. Therefore, the eradication of salmon from such large regions of Nova Scotia will probably hinder future programs to re-establish salmon in their former range when pollution of the atmosphere is eventually contrtolled and the acidity of rain reduced.

In summary:

(1) All rivers of pH less than 5 show a decline in angling returns beginning in the 1950's. Similar Nova Scotian rivers of pH greater than 5 show no trend in angling returns since 1936.

(2) Electrofishing has verified that juvenile Atlantic salmon are absent from waters of pH less than 5, populations are low in the pH range 5.0-5.4, and normal populatons are present in waters of pH greater than 5.4.

(3) Tag return and habitat data indicate that the Atlantic salmon losses attributable to acidification amount to 33% of Nova Scotia's total salmon production potential (average of 23,000 salmon/year).

RESEARCH

I. Westfield River Ecological Study

An intensive study of fish ecology, with emphasis on Atlantic salmon production, was initiated on the Westfield River in 1980. This river, a tributary of the Medway River in southern Nova Scotia, was selected as a model system to monitor the anticipated loss of salmon stocks and to do research on certain aspects of salmonid biology. The river chemistry (annual pH range of 4.6-5.4 with <1 ppm Ca, >10 ppm DOC, and >200 ppm dissolved Al) was considered marginal for reproductive success for salmon. Westfield tributaries and adjacent river systems presented a range of chemical conditions ideally suited for comparative studies.

Initially, three precipitation gauges were installed in the Westfield drainage, and the Westfield and two tributaries were gauged to provide hydrological data. Weekly water samples at the three gauge sites provided chemical data for modeling and monitoring purposes, and to provide background data for the research programs.

These comprehensive studies of the effects of the pH of Atlantic salmon rivers in Nova Scotia have, since 1980, yielded considerable information concerning the fate of salmon in these acidic streams, a solid data base pertaining to the chemistry of this river system and concomitant status of the fish and invertebrate biota - well suited to a continued monitoring program.

Juvenile Atlantic salmon are the most abundant fish at study sites where pH levels never decrease below 5.5. Densities and biomass of salmon are significantly reduced in rivers where pH levels fall below pH 5.0 for part of the year, and the species is absent in rivers where pH levels are continuously less than 5.0. Survivorship curves for Atlantic salmon indicate periods of increased mortality related to low pH (<5.0) during egg incubation, following fry emergence, during overwintering as parr, and during smoltification.

Hatching success of Atlantic salmon embryos incubated in the natural substrate of streams with mean pH of 4.5-5.0 is possibly correlated with the pH of interstitial water percolating through the substratum. Embryo mortality was 25% at mean pH 5.0, and about 50% at mean pH 4.7. Emergence of salmon fry from natural redds is reduced at pH 4.8, indicating alevin mortality.

Densities of salmon parr, one month after emergence, are markedly reduced at study sites with pH 5.0 - the reduced densities resulting mainly from high mortality of post-emergent fry during transition to exogenous feeding (70% in 30 d at pH 5.0). Increasing the pH to 6.0 by treatment of stream water with limestone reduced mortality to 5% and eliminated behavioral abnormalities (reduced feeding and activity) and decreased body ionic content.

Physiological responses of juvenile salmon in the Westfield River at pH less than 5.0 (increased hematocrit, decreased plasma Na and Cl) are similar to those reported in laboratory studies. Salmon smolts appear to be more sensitive to low pH than parr, and 0+ parr are more sensitive than 1+ parr. The overwintering mortality rate of 0+ parr is much higher at sites where the pH is <5.0 from November to April. Densities of 1+ parr were $<2/100\ m^2$ in the Westfield, compared to about $10/100\ m^2$ in a La Have tributary, a river ca. 150 km to the northeast, with pH always above 5.5. Some of these differences may be due to downstream migration of older parr from the Westfield to the Medway, which is about 0.5 pH unit less acidic.

Using caged fish in various Westfield tributaries, marked toxicological, physiological and behavioral effects on salmon parr were attributed to H^+ as the pH fell below pH 4.7 during autumnal low pH precipitation episodes. Metal (Al and Fe) accumulation on the gills was ruled out as a lethal factor.

As a result of cumulative mortality, annual production rates of juvenile salmon in the Westfield are very low ($<50\ g/100\ m^2/yr$) with negligible smolt production ($<1/100\ m^2$) in the Westfield River. In comparison, production rates in a stream at pH >5.5 produced $100\text{-}200\ g/100\ m^2/yr$ with 4-8 smolts/ $100\ m^2$. The Westfield salmon population still persists probably because of contributions of stray spawners ($>70\%$ of all spawners) from enhancement programs operated in less acidic parts of the Medway drainage.

Benthic macroinvertebrate communities in the Westfield study areas are characterized by lower mayfly and caddisfly, but higher Diptera diversity and abundance at sites where mean pH levels are <5.0. Total annual production however, only differ by 11%. As a result of these differences, species composition in juvenile salmon diets differed in more acidic sites, but there was no appreciable differences in amounts of feed consumed by fry inhabiting streams of pH <5.0 and streams of pH >6.0. Some of the above observations must be qualified by the fact that the Westfield River had more dead water areas upstream of the study site than did the high pH site on the LaHave system. This may have contributed to some of the observed species composition differences. The lower salmon density in the Westfield may also have had an effect on amounts of food consumed.

The intensive ecological studies conducted in the Westfield River project and research plans fill in an important knowledge gap in the spectrum of North America programs. They primarily provide an important information link between synoptic surveys and laboratory-based research, and serve to verify the accuracy of quantitative models of the biological response to acidification usually proposed from these surveys and laboratory experiments. The project is one of the few integrated chemical and biological studies of acidified riverine ecosystems and the only comprehensive study of Atlantic salmon populations in these systems. Its relative proximity to DOE Kejimkujik studies and Atmospheric Environment Service LRTAP Monitoring programs (i.e. APMON) allows the fisheries database to be developed in close association with a broad-scale environmental monitoring of airborne pollutants and water quality.

II. Adult Salmon Maturation Studies

Studies on maturation processes occurring in adult Atlantic salmon have been continuing since 1981. These have focussed on certain critical hormones, which regulate the physiology of animals including fish. For example, in males the androgens are essential for the promotion and maintenance of spermatogenesis. In normal Atlantic salmon the androgens 11-Ketotestosterone (11-KT) and Testosterone (T) became greatly elevated during the last few months of sexual maturation, peak at function maturation and decline thereafter. Any deviation from this normal hormone metabolism is indicative of reproduction problems.

In our study, the effects of the low pH Westfield River (pH range 4.6-5.3) on sexual maturation, androgen production, reproduction, weight gain and steroid hormone metabolism in the Atlantic salmon were compared with those from similar fish in the more normal less acidic Medway River (pH range 5.4-6.1). A comparison of androgen levels revealed that plasma T and 11-KT levels in the acidic Westfield River fish were significantly lower ($P<0.001$) than those in the Medway River fish. These results indicated abnormal sex hormone metabolism in the Westfield fish. In mid-July, 1982, 108 sexually maturing 2-yr Atlantic salmon were divided into two groups of equal numbers of each sex. One group was placed in a cage in the Westfield River (pH 5.1-5.3) and the other in the less acidic Medway River (pH 5.4-6.2) and were held for a few months until after sex maturation. The fish were fed daily and periodically the fish were anaesthetized, weighed and blood samples were taken for homone analysis. Blood T and 11-KT levels were determined by radio immuno-assay, which showed that mean plasma T levels in sexually maturing male Atlantic salmon held in the Medway River increased during maturation, peaked at functional maturity and declined after spawning as normally occurs in salmonids. By contrast, mean plasma levels in the Westfield River fish did not correlate with the approach of functional maturity and remained high after spawning. The abnormal sex hormone metabolism in the Westfield River fish is indicative of a reproduction problem. Mean plasma 11-KT levels in both Medway and Westfield male salmon increased with approaching sexual maturity as normally occurs in salmonids, but in the low pH Westfield River fish, 11-KT decreased more sharply at the end of functional maturity (spawning) than in the Medway River fish. Biosynthesis of steroids (in vitro) from precursors ^{14}C-progesterone and ^{3}H-pregnenolone by testes from sexually mature Atlantic salmon held in the two rivers showed low production of 11-KT by testes of Westfield River fish. These results agree with blood androgen levels. Biosynthesis of steroids (in vitro) from precursors ^{14}C-progesterone plus ^{3}H-pregnenolone by head kidneys (adrenal homologues) showed high production of B (corticosterone and low production of Reichstein's S, (11-deoxycortisol) in the acidic Westfield River fish and the reverse of this pattern in the Medway River fish. This abnormal pattern in the Westfield River fish is indicative of stress. As in all salmonids, cortisol (F) is the principal corticosterone in the fish in both rivers. Although there was less rainfall in the summer and fall of 1982 than in 1981 resulting in higher pH's in the Westfield River in 1982, the Westfield fish showed a smaller weight gain and mean egg volume when compared to Medway fish. The fecundity (number of eggs per unit weight of fish) was 31% less in the Westfield River salmon than in the higher pH Medway River.

In 1984-85, approximately 150 sexually maturing Atlantic salmon were divided into two groups of equal numbers of each sex, again with one group being held in the acidic Westfield River and the the other in the more normal Medway River as a control group. These fish were held during the last 2½ mo of their sexual maturation process. During this time, the fish were fed daily. Blood samples were taken for hormone analysis every 2 wk as in previous experiments. Salmon held in the Westfield gained less weight, produced fewer and smaller eggs (females had 31% less fecundity) and both males and females had abnormal sex hormonal metabolism. In a 2-d period, 23% of the post-spawned Westfield fish died when the pH fell to 4.7. The remaining fish all survived upon transfer to the Medway River. In 1983, 75% of similar Atlantic salmon died over a few days when the same conditions occurred in the Westfield River and the fish were not removed immediately to a higher pH river. The die-off of post-spawned salmon in the acidified river suggests that wild stocks may be suffering an additional and hither-to-now undiscovered impact.

We have recently developed a new radioimmunoassay (RIA) method for determining 17-alpha, 20-beta-dihydroprogesterone in plasma of female salmon. Using this method in 1985, we have shown that this hormone is one of the principal female sex hormones in Atlantic salmon, peaking in the blood at the point of sexual maturation. Salmon held in the Westfield River did not demonstrate this normal response, thus showing that both male and female salmon are affected by acidic waters.

In 1985-86, a number of outside collaborators (see Appendix II) were invited to study various aspects of the fish, to assess various sublethal tests as indicators of acid stress, at the two cage sites when the fish were sacrificed in November 1985. Most of the results have not been released. The histological study of atherosclerotic lesions in the coronary arteries indicated no difference between fish held at the two sites. Length of time in fresh water appeared to be a more important factor than the location of the cage site.

III. Laboratory Studies

Laboratory studies have concentrated on investigating the sensitivity of the various stages of the Atlantic salmon life cycle to low pH. Particular attention has been devoted to early development and parr-smolt transformation. Since the work on early development will be reviewed in a separate presentation (R. H. Peterson), it will be given only a brief treatment here. Exposure of Atlantic salmon eggs to low pH can reduce water uptake during the hardening process, inhibit or delay hatching and can change the physical strength of the chorion so that it is not easily shed by the hatched alevin. The hatching period is frequently a stage of increased mortality at low pH. Hatching is one of the most sensitive processes as it can be significantly delayed at pH levels as high as 5.5. Delay of hatching may have survival value during low pH events in the newly hatched alevins are less tolerant of low pH than are late-stage eyed eggs. Reduction in water uptake during the hardening process has a pH threshold near pH 5.0, as have many other effects of low pH on salmon physiology.

Low pH affects the development of hatched alevins by decreasing growth rates, reducing the conversion efficiency of yolk-to-embryo material transfer, and by interfering with normal action exchanges with the ambient medium. These processes may be interrelated. Again, the threshold for the observation of these effects is about 5.0.

Smoltification, the sum total of physiological adaptations related to survival in sea water, does not proceed normally in parr living in water of pH less than 4.9. The mean results of exposure to low pH is a decrease in blood Na^{+}, Ca^{2+} and Cl^{-}, which has been shown generally for several species of teleost - and blockage of the increase in gill Na^{+}-K^{+} ATPases required for the acquisition of salinity tolerance. The two phenomena are no doubt related. There is also some apparent loss of appetite and associated change in energy metabolism - changes which may result from loss of blood electrolyte.

Providing pre-smolts with a salt-enhanced diet appears to mitigate many of the effects of exposure to pH as low as 4.7. This may be useful in certain situations for hatchery reared fish, but will hardly be useful in protecting wild fish.

We lack knowledge of the importance of the influence of low pH on smoltification to wild populations. No analyses have been performed on smolts migrating to sea in the spring to see if salinity tolerance (or lack thereof) is a problem. Utilization of refugia at higher pH may be important for overwintering pre-smolts. Although the evidence is not very good, it seems probable that most large parr migrate from the Westfield into the Medway at a somewhat higher pH before becoming smolts. Whether migration of large parr out of more acidic tributaries is a general phenomenon is unknown.

MITIGATION

The aim of this program is to assess the practicality (technical and economic) of restoring acidified Atlantic salmon habitat by river liming. In this connection, the Department of Fisheries and Oceans has undertaken experiments to test the feasibility of establishing high pH refuges in some acid rivers by addition of limestone or other substances to lakes or streams. This technique is being considered as an interim measure to preserve the genetic characteristics of the salmon populations that will be needed in the future to recolonize former salmon rivers in the Atlantic Upland region of Nova Scotia. A separate report will be presented by W. D. Watt on this subject at the Workshop.

The experiments conducted to date indicate that the pH of salmon streams can be adjusted to satisfactory levels by liming, but that fresh lime must be added annually and in some cases, twice annually. Various different liming methods have been tested and estimates have been made of the relative costs and effectiveness. The two liming approaches most thoroughly investigated to date are: the use of instream limestone gravel deposits, and the liming of headwater lakes.

Results from three years of experiments with instream limestone gravel can be expressed in the form of the following equation:

$$pH = 0.237\ (\log_e \mathrm{DOSE}) + 0.008\ (^\circ C) - 0.809$$

where pH represents the rise in pH to be expected for a given limestone gravel DOSE (in metric tonnes per m^3s^{-1} of discharge) and temperature. The calculated r^2 is 0.84. The effectiveness of instream limestone gravel is inversely related to flow and is significantly reduced at low temperatures. Under winter conditions, tonnages of limestone that would theoretically be required to ensure satisfactory pH levels are so high as to be impractical.

Satisfactory levels of pH can be achieved in salmon streams if the headwater lakes are treated with powdered limestone doses of about 3 times the lake acidity. Because of the low mean residence times in most Nova Scotian lakes, retreatment would be required on an annual basis. A major problem with this approach has been the advent of midwinter rain storms, the runoff from which accumulates as a low pH surface layer on the limed lakes and delivers a low pH shock to the salmon juveniles in the outlet streams. During the winter of 1983-84, this problem was overcome by the expedient of spreading a layer of powdered limestone over the ice.

In terms of relative costs, the instream limestone gravel approach would cost approximately $500 per returning salmon in Nova Scotia rivers while headwater lake liming costs are about $150 per returning adult salmon. Even at $150 per salmon, it is evident that this approach is not economically feasible for a full-scale salmon restoration effort in all of the 26 salmon rivers presently impaired by acid rain.

In summary:

(1) The technical practicality has been successfully demonstrated on a pilot scale.

(2) Cost/benefit analysis indicates that to restore the lost Atlantic salmon production in Nova Scotia's acidified rivers by liming would cost four times what the resource is worth (approximately $400/restored salmon).

ROYAL SOCIETY OF CANADA - GENERAL OBSERVATIONS
REGARDING THE FISHERIES RESEARCH

The Royal Society review panelists made very few specific criticisms of the Scotia/Fundy programs (Appendix III). That of P. J. Dillon, regarding primary and benthic productivity, is addressed below. Most critics thought the laboratory programs and Westfield study were well conceived and productive. One critic thought that the laboratory programs might be receiving insufficient funding. This shortage has been corrected in a rather ironic way, since the Royal Society review in 1984. Funding has frequently come so late in the fiscal year in the last 2-3 yr, much of the Westfield field program has necessarily been deferred or curtailed. Some of the money earmarked for the Westfield field studies has therefore supplemented aspects of the laboratory programs. The panelists' comments regarding manpower shortages for research are even more applicable now than they were at the time of the review.

One of the few criticisms directed at the Westfield program by some of the Royal Society reviewers pertained to implementation of studies on lower trophic levels (e.g., primary production). When the Westfield program was first conceived, we had the somewhat ambitious objective of looking at the relative importance energetically of primary production, allochthonous energy sources, and of energy derived from anadromy. Since these Nova Scotian streams are nutrient deficient, we considered that mortality of anadromous spawners (alewives, salmon, lampreys) could be a significant nutrient source. Loss of this source through acidification could result in lower productivity. We agree that this objective was probably too ambitious; primary productivity studies were discontinued after the first year. We may be able to attack this problem as a paper exercise, using the database we have accumulated in the Westfield System.

Regarding the mitigation project, one reviewer thought that the project was a muddled repetition of work already done in Sweden. In this regard, it should be pointed out, however, that the Swedish experience is mainly with lake liming, and what river liming has been done has involved the use of various mechanisms for a riverside lime storage and continuous river dosing. These systems are very dependent on year-round road access and (on the scale required for a salmon river) require a reliable electric power supply. No attempt has been made to repeat this Swedish work in Nova Scotia (though the U.S. in repeating it now in Virginia). The DFO program concentrated instead on instream applications of limestone gravel and headwater lake liming. The Swedish data on river dosers has been included in the DFO reports.

Another comment came from a reviewer who felt that DFO had developed innovative liming approaches in its mitigation program, and suggested using liming as a tool in an experimental design for elucidating aquatic biota responses to acidification. This recommendation was not followed up on, because it was not compatible with the primary goal of the study and would have required more assured resources.

COMMENTS ON RELATIONSHIP OF THE SCOTIA-FUNDY REGION'S PROGRAMS TO OTHER PROGRAMS

National Inventory

This was a regional component of a national program. A general synthesis of all the regional data bases was prepared by J. R. M. Kelso. Similar surveys are performed by EPA in the U.S. and by SNSF in Norway.

Westfield River Study

The water chemistry of the study site and the nature of the studies combine to make this a comprehensive and unique study of Atlantic salmon production. Studies are also being initiated in Quebec with streams which have quite different hydrologies and climatology. Streams in Newfoundland are not so acid stressed. Linkage with laboratory studies also contributes to uniqueness.

A work session on the Westfield River with a number of invited scientists, regional, national and international, have participated in some of the Atlantic salmon experiments on the river, as mentioned earlier (Appendix II). This cooperative research allows additional expertise to be brought to bear on the acid rain - Atlantic salmon problem.

Laboratory Studies

Few laboratories elsewhere study the influence of low pH on Atlantic salmon development and physiology. Some similar work on acid toxicity to yolk-sac fry and smolt have been performed in Norway.

PROPOSED FUTURE RESEARCH

Proposed future research activities fall into four major areas and are described briefly below. These include: 1) monitoring, a vital component in the framework design of all impact assessment studies; 2) continued comprehensive research studies in the Westfield area, a significant contribution to a holistic approach; 3) mitigation, a necessary tool to reduce or eliminate environmental impacts; and 4) complementary studies on airborne contaminants of aquatic resources.

I. Monitoring

A chemical and biological (electrofishing) monitoring program will be maintained on rivers where the Atlantic salmon runs are believed on the verge of extinction. Our plans are to continue this activity even after the establishment of an international agreement of emission controls; so as to evaluate the effectiveness of the controls program, and to monitor the process of deacidification.

We recommend redirecting some monitoring and research effort toward the other anadromous species, and giving attention to detecting changes in zoogeographic distributions of freshwater species. There is a good historic data base for Nova Scotia zoogeography of freshwater fish, dating from the 1950's.

II. Westfield River Research Studies

For the Westfield River ecological study, we propose to continue monitoring of fish populations (juvenile salmon and other species), macroinvertebrates, and of water chemistry in the river and nearby streams over the pH range 4.5-6.5 to assess the long-term performance of populations adversely affected by acidic conditions, their response to possible future changes in acid deposition levels, and the natural variability in biota inherent to these ecosystems (i.e., background noise). Intensive monitoring of a few systems selected to provide a spectrum of spatial variability would also provide answers to specific research questions and an evaluation of the generality and applicability of findings from previous studies in the Westfield and adjacent river systems in southern Nova Scotia.

We also propose further research efforts to quantify the chemistry of organic waters and its effect on the biota to evaluate the toxicology of acidity from different sources. Research at the ecological level will examine the importance of acidity related movements and other significant behavioural responses by juvenile salmon and other biota, the constraints of river acidity on their distribution and habitat utilization, and the interaction between population density and life-table parameters in acidic rivers. Research aspects of this program often go hand-in-hand with the chemical and biological monitoring program described, thus optimizing resource allocations.

This year we plan to conduct a two-cage experiment holding adult Atlantic salmon in the acidic Westfield River, one being exposed to the usual acidic water while the other would be exposed to the acidic water treated with lime (plus one control in the high pH Medway River). Investigations would be carried out on the water chemistry to determine the relationship between pH, calcium, aluminum organics and other components in the river water and their relationship with toxicity. Much of the river water in the Westfield system comes from bog areas and it is certain that the organics in this pH-influenced dynamic system plays an important part in the water toxicity. The information obtained will be useful in mitigation and monitoring the effect of mitigation. Most of the outside participants from the 1985 study have expressed interest in participating in our studies and from these we are hopeful that we can have a documented comprehensive summary of the various biological biochemical effects of the river water on the Atlantic salmon.

One of the difficulties with this research is that it is difficult to extrapolate these findings on caged, feeding fish to wild adults which cease to feed after migration to freshwater. More studies should be done on wild fish to allow comparisons to be made. Egg deposition and quality of eggs deposited by wild fish should also be investigated more carefully.

There is one assumption that we would like to test in 1987. It is assumed that simply stopping the input of acidifying materials to the watershed would allow for successful reproduction or rejuvenation of the streams. It is assumed that the stream would return to pre-acidification characteristics. It is possible that the years of acid treatment of the watershed has removed most of the materials which would be responsible for this return and such a return would be delayed until the materials were replaced, if indeed they were within a non-geological time frame. We would like to determine if adjusting the pH back to the 5-6 range using a non-calcium base is equally efficacious. For example, even when offered a diet containing sodium fortification and taste enhanceers, salmon held in the Westfield did not feed and grow anything like normal.

III. Mitigation

The preliminary feasibility studies have now been completed for the liming program, and it is our desire to proceed with a full-scale demonstration project to establish a deacidified refuge for a threatened salmon stock. East River (Chester) is our target for the first refuge. The current plan calls for establishing at least two other deacidified refuges in areas where widespread extirpation of salmon runs is anticipated.

A noted decline in dissolved organic carbon concentration in acidified rivers may herald the advent of aluminum toxicity problems. Currently, the high aluminum levels are detoxified by chelation with the DOC component. We propose to carry out further investigations as to the relationship between Al-DOC complex formation and toxicity to salmonids, including potential mitigation methods.

Given the successful completion of the above proposed projects, we feel that the status of Atlantic salmon vis a vis acid rain will be well established, and DFO will then no longer need to pursue this as a major research goal.

IV. Airborne Contaminants on Aquatic Resources

Long range transport of organochlorine compounds such as PCB, toxaphene, and chlordane, and of polynuclear aromatic hydrocarbons is documented, but the data are insufficient for an accurate assessment of quantities transported by this mechanism. At the same time, the list of compounds subjected to this transport is incomplete. In addition, questions such as "wet" versus "dry" fallout, transport in the vapor phase versus transport on particulates and chemical transformation during the transport have not been answered.

Chemical analytical techniques for most organic compounds likely to be found in atmospheric fallout are mostly available. The instrumentation and the implementation of these techniques is costly. Nevertheless, a screening and monitoring systems should be put in place to determine the identity and quantity of organic chemicals subjected to long range aerial transport.

APPENDIX I

SCOTIA-FUNDY REGION

ACID RAIN PUBLICATIONS

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APPENDIX II

List of Participants and Their Activities During the 1985 Acid Rain/ Caged Atlantic Salmon Experiment-Westfield and Medway Rivers, Nova Scotia

Participants and Affiliations	Activities
H. C. Freeman, G. B. Sangalang and L. Sperry DFO, Halifax	Weight gain, sex hormone levels and metabolism, stress hormone metabolism, egg and sperm viability, post-spawning survival. Water quality
H. Rosenthal, G. Batt, J. F. Uthe, C. J. Musial ARL, NRC and DFO, Halifax	Egg hatchability, fry meristics and gross pathology
Trevor Goff, Mersey Hatchery DFO	Fecundity, egg volume, spermatocrits, hatchability
Dave Idler, MSL U of Nfld., Logie Bay, Nfld.	Protein hormones in blood vitellogenin, ACTH-types
Vic Cairns, Mike Whittle CCIW, DFO, Burlington	Spinal abnormalities, curvatures, compressions, dislocations
H. McCormick, R. Leino EPA, Duluth, Minn.	Gill arch and head kidney histology
T. Haines, C. Jagoe U. of Maine. Orono	Gill ultrastructure and blood ions
H. Harvey, M. McArdle U. of T, Toronto	Plasma ions, muscle
J. Klaverkamp, H. Majewski, R. Evans, S. Brown, and L. Lochart, D. Metner FWI, DFO, Winnipeg	Metallothionein, blood hormones, thyroxine, glucose, lipids, ions, Olfactory rosette histology, gill, liver and kidney histology
J. Uthe, C. Chou DFO, Halifax	Toxic elements in gills, liver and kidney
R. Saunders, DFO, St. Andrews, N.B.	Aortic arch histopathology
J. Payne, L. Fancy, U. Williams DFO, St. John's	Mixed function oxidase in gills and liver

APPENDIX III

Reviewers' Comments on Various Fisheries Research Branch Scotia-Fundy Region LRTAP Projects Arising from Royal Society of Canada - A Peer Review of Canadian Federal Research, 1984

1. D. J. Dillon

DFO (6-7) (Lacroix, Peterson)

P. 5, para 3: The Westfield Basin fisheries project is collecting useful long-term and short-term data. However, more attention needs to be paid to aluminum chemistry, perhaps at the expense of much of the trophic level work. I am not at all clear why primary production and benthic production are being measured.

DFO(8,9,24) (Peterson, Freeman)

P. 5, last para: The fish physiology studies were interesting and seemed to be making good progress.

2. G. E. Glass (No specific comments on Scotia-Fundy projects)

3. E. Gorham

DFO (5-8)

P. 10: The calibrated watershed program across a gradient of acid deposition is also well conceived. The watershed program should also be assured of a life-span of at least 25 years to exploit its potential adequately; the Hubbard Brook ecosystem studies are clear evidence of the need for and value of such long-term support.

DFO (6,7) Lacroix, Peterson

P. 11, last para: Among the remaining projects, I have been particularly impressed by the microbiological/biogeochemical studies (DFO 18), the use of isotope geochemistry as a tool in understanding the acidification process (IWD 25-27), the investigations of salmon physiology, the Kejimkujik studies (CWS 4, IWD 8) that turned up the problems with sulphate analyses in coloured waters and the great importance of considering coloured waters in the context of acid deposition, and finally the experiments with liming (DFO 11) as a means of developing refugia for genetic salvage of salmon stocks.

General - P. 12: The most glaring weaknesses of the whole program (and not only the aquatic portion of it) is the lack of an overall, coherent plan to which individual projects are related (cf. my categorization of aquatic projects in Table 1). Such a plan is urgently needed to provide a basis for project coordination across disciplines and across the country, and to identify scientific and geographic gaps in the overall program.

Appendix III (cont'd.)

4. T. A. Haines

General - P. 19, last two paras: Properly located and operated calibrated watersheds would be a powerful research tool and could become the focus of all LRTAP research efforts. At the present time, a great deal of resources, both human and financial, are being expanded on projects conducted in isolation.

P. 19, 2nd para: Given the present apparent importance of pH-calcium-aluminum-dissolved organic carbon interrelationships in determining the development of conditions toxic to aquatic biota, this aspect of research is very greatly under-represented in the LRTAP program.

5. J. R. Longcore

General - P. 23, 2nd para: These studies vary with the responsibilities of the agencies involved and range from investigations of direct effects of low pH on fish to concern about waterfowl foods (invertebrates). There is need for experimental study and many of these special projects filled that role. Interpretation of results, however, must be done with caution because laboratory studies cannot fully duplicate field conditions. Nevertheless, some of the ecotoxicological studies have been useful in detecting sublethal effects in organisms. It seems that if the research can reveal these sublethal effects then we are in a better position to prevent further biotic losses and thereby maintain the integrity of natural systems.

6. T. Nudds

General - P. 42, 2nd para: 5.1 The LRTAP program, as a whole, reflects characteristics of research in the early, immature stages (i.e., there is a heavy emphasis on description rather than testing). This is a necessary prerequisite in order to meet LRTAP objectives, but during the next funding period, more emphasis must be placed on using data to evaluate and link deposition to ecosystem changes. That can only be done, and be scientifically sound, by testing hypotheses.