Evaluation of The RAIN Project

Reversing Acidification in Norway

Report prepared for the Programme Committee on Transport and Effects of Airborne Pollutants (TVLF)

November 1991

Nasjonal komité for miljøvernforskning

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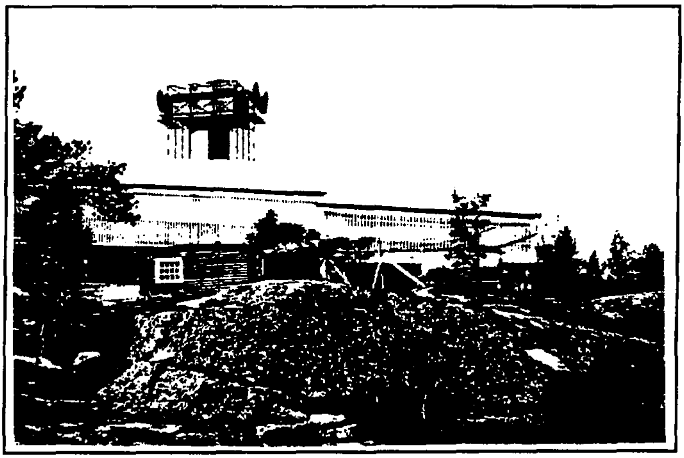

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Photo on page 2:
At Risdalsheia ambient acid rain is intercepted by means of a roof, treated by filtering and ion exchange, and then automatically sprincled beneath the roof. At a second roofed catchment (control) the acid rain is recycled. Six years of acid exclution have caused major changes in runoff chemistry relative to the control and reference catchments.

Index

Summary

This report presents a scientific assessment of the RAIN project. It describes the main hypotheses tested and the applied methods. The major results of the research are highlighted and discussed, and they are placed in the perspective of national and international acid rain research. An important part of the RAIN project has been to provide information to the public about the acid rain problem, and in this way it has performed an important background role in influencing political decisions and legislation. The RAIN project is regarded as a cost effective research effort, and the novel approach and capital investment will enable further manipulation studies at these sites in the future. It is recommended that the project is continued in the immediate future, with some modification to answer specific questions resulting from the collected data.

Mandate and composition of the evaluation group

The Programme Committee on the Transport and Effects of Airborne Pollutants (TVLF) is organized by the National Committee for Environmental Research (NMF) and works in cooperation with the three research councils Norwegian Research Council for Science and the Humanities (NAVF), Agricultural Research Council of Norway (NLVF), and Royal Norwegian Council for Scientific and Industrial Research (NTNF). TVLF has a responsibility for coordinating research funded by NMF and the three research councils within the field of transport and effects of airborne pollutants. Planning and evaluation of research activities are parts of these responsibilities. Since 1982 the RAIN project has received extensive financial support from Norwegian sources, including the TVLF committee. With the present organization of funding committees it has been the responsibility of the TVLF committee to initiate an evaluation of the RAIN project.

The aim of the evaluation, and the mandate of the evaluation group, is to perform a scientific assessment of the Norwegian research efforts within the RAIN project. In particular the role of the project in national and international research should be emphasized as well as the impact of the project on environmental protection authorities.

The composition of the evaluation group was as follows:

William Dickson	*Swedish Environmental Protection Agency*
Alan Jenkins	*Institute of Hydrology, Natural Environmental Research Council (UK)*
Lennart Rasmussen	*The Technical University of Denmark*
Arne Stuanes	*Chairman of the TVLF Programme*
Frode Stordal (secretary)	*Secretary of the TVLF Programme*

The evaluation group participated in a RAIN project meeting in Grimstad as well as a site visit to Risdalsheia 17.6.91. Interviews with the project manager and project scientists were held at NIVA 18-19.6.91

Background

The concept of the RAIN project grew out of the results of the 1980 Sandefjord conference. Sandefjord marked the end of the SNSF-project. The relationships between emissions of SO_2 and NOx, long-range transport, deposition of acidifying compounds, acidification of lakes and rivers and loss of fish populations and damage to other aquatic organisms appeared to be quite well established, at least empirically. The situation was similar in Europe and North America, with large emission sources in major industrialized countries and remote, sensitive receptors in less-powerful countries. Most countries in both Europe and North America had agreed to reduce SO_2 emissions by 30% by the year 1993 relative to levels in 1980. This formed the so called "30% club" under the auspices of the Convention on Long Range Transboundary Air Pollutants under the United Nations Economic Commission for Europe.

Yet in 1980-81 there was very little information available regarding the reversibility of acidification of freshwaters. For decades emissions had been increasing, acid deposition had been increasing and spreading to new areas, and more and more lakes and rivers were experiencing damage to fish populations. The reductions in emissions were in part based on the assumption that such measures would ameliorate the acidification problems and protect the environment against further damage. But apart from "back-of the-envelope" calculations and simple empirical models there was at that time little hard evidence to answer questions such as; To what extent is acidification reversible? How long will it take? Does recovery proceed along the same path as acidification, or are there lags and hysteresis? Is the present acidification in southernmost Norway enough to cause acid runoff in more pristine parts of Norway?

Main hypotheses

The following main hypotheses were put forward for the project at the ecosystem level:

- Acidification of soils and freshwater can be reversed by reduction of atmospheric inputs of strong acids.
- Increased atmospheric inputs of strong acids will lead to increased soil and freshwater acidification.
- In sensitive ecosystems the response of changes in atmospheric inputs of strong acids will be rapid and detectable within a period of a few years.
- Fish populations can be restored to acidified freshwaters by removal of the atmospheric input of strong acids.

These hypotheses are simple, easily perceivable and of general scientific value. An additional list of hypotheses have been directed at the process level and also for individual satellite projects, but they are not repeated here.

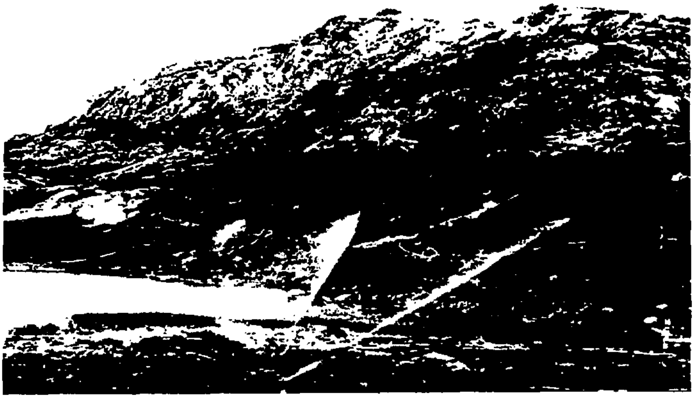
Objectives

The objectives of the RAIN project have been, by whole ecosystem manipulation, to quantify the effects of removal or addition of strong acid inputs to catchments, in particular to answer the questions;

- Is acidification reversible?
- What level of recovery can be expected?
- How quickly will reversibility occur?
- Are there lags and hysteresis effects between acidification and recovery from acidification?
- Will input of acidity at levels currently observed in southernmost Norway cause soil and water acidification in similar but unacidified areas of Norway?

Methods used to achieve the objectives

The project comprises two parallel large scale experimental manipulations of natural headwater catchments to determine the response of runoff chemistry to changes in the loading of strong acids from the atmosphere. The chosen locations of the study catchments are considered most suitable to this study. The sites are characterized by thin soils which are sensitive to acid inputs and are representative of large areas of Norway. The ecosystems are relatively simple in that functional changes may be readily observed and quantified. There are also a number of small catchments suitable for such manipulations available at each of the two locations.



In Sogndal seven years of acid addition to two catchments have caused major changes in runoff relative to untreated controls.

Site characteristics of the increased loading experiments at Sogndal are; a low level of acidic deposition (pH greater than 4.7), low weathering gneissic bedrock, thin and patchy soils with alpine vegetation at an elevation of 900 m.

The acid application consists of additions to the surface of the snowpack in winter and additions of simulated rainfall during summer. The pH of water applied during summer is 3.2 which is possibly too strong and may cause high leaching. Precipitation pH values of around 3.2, however, are found at Birkenes during episodes. The added load of sulphuric and sulphuric plus nitric acids per square meter, however, are ambient at Birkenes and therefore relevant.

Site characteristics of the decreased loading experiment at Risdalsheia are; highly acidic deposition (pH 4.3), slowly weathering granitic bedrock, thin and patchy soils and a sparse forest of pine and birch at 300 m elevation.

The experimental design consists of two roofed catchments, one receiving clean rain and the other receiving ambient acid rain. A further catchment, without a roof, also receives ambient acid deposition. The experimental roofs and the roofed and unroofed controls give excellent possibilities for comparison of results.

In summary, the experimental design is good and scientifically sound. The frequency of sampling and analysis undertaken is sufficient for the main objectives to be achieved. We agree that the establishment of a control roof has aided the interpretation of the experimental results and was a worthwhile investment.

The main scientific findings

At both Risdalsheia and Sogndal there have been expected results, but also some surprises.

In short the results have been:

Risdalsheia

— reduced sulphate, nitrate and ammonium in runoff
— alkalinity increases
— slow soil recovery but not detectable in the soil solid phase
— only minor increase in pH
— constant amount of total organic carbon in runoff but an increase in the dissociation of the organic acids giving a strong buffering effect
— runoff is still toxic to fish

Sogndal

— acid addition causes acid streamwater
— sulphate goes up and pH and alkalinity go down in runoff
— slow acidification of soils but not detectable in the soil solid phase
— water toxic to fish
— incipient "nitrogen saturation" after only five years addition of nitric acid
— increased leakage of nitrate due to sulphuric acid addition

At both Sogndal and Risdalsheia the change in acid deposition caused major changes in runoff chemistry.

At Sogndal runoff was acidic with high concentrations of sulphate and aluminum occurring during the first snowmelt in spring 1984. Addition of acid to this catchment in amounts similar to the input load at Birkenes has clearly influenced the chemistry of runoff water (Figure 1 and 2). In 1989 the signs of "nitrogen saturation" appeared at the catchment treated with an addition of a mixture of sulphuric and nitric acid. Nitrate concentrations remained significantly high for several weeks following the application of acid in October. This continued in 1990. In 1990 nitrate concentrations in runoff from the catchment receiving only sulphuric acid were above background levels for much of the summer and autumn. This is clearly an indication of disruption in the nitrogen cycle in the terrestrial part of the catchment.

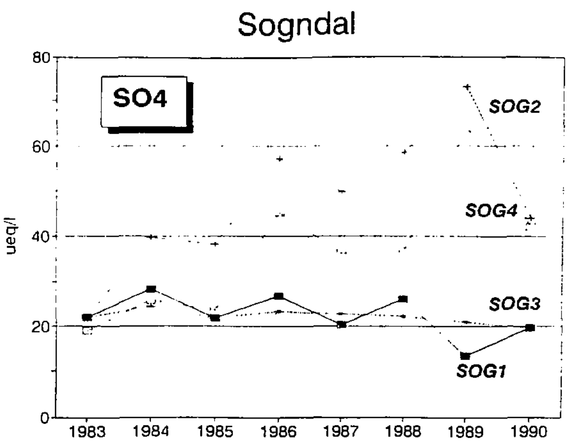


Figure 1:
In Sogndal sulphate has increased by about 40 eq/l from 1983 to 1989 in the catchment where sulphate (SOG2) has been added, and by about 20 eq/l where nitrate as well as sulphate (SOG4) have been added.

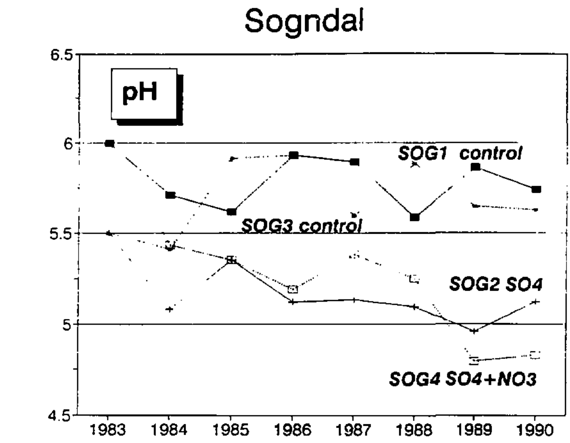


Figure 2:
In Sogndal pH has decreased from >5.5 to about 5 in the catchments with acid addition.

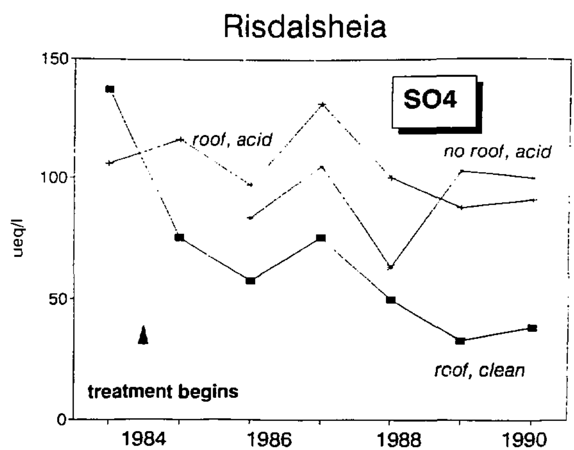


Figure 3:
At Risdalsheia sulphate has decreased from about 100 to about 40 eq/l in the roofed catchment.

At Risdalsheia acid exclusion resulted in an almost immediate decrease in nitrate and ammonium concentrations in runoff. Sulphate concentrations began to decrease late 1984 and have continued to decrease in subsequent years (Figure 3). The decline in strong acid anion concentrations has been compensated by a decline in concentrations of base cations and by an increase in alkalinity.

The pH values in runoff at Risdalsheia (Figure 4) have increased only slightly in spite of the decrease in strong acid anions. The output of total organic carbon has been almost constant but the degree of dissociation of the organic acids has increased and buffered against pH changes in the highly-coloured runoff. These results confirm earlier results from lysimeter experiments with almost the same type of soil.

The trends in sulphate concentrations and fluxes at both Sogndal and Risdalsheia indicate that the soils have a significant but limited capacity to retain and release sulphate and thus regulate concentrations of sulphate in runoff. Sulphate released by mineralization has not been studied.

Input-output budgets indicate that the pool sizes of exchangeable base cations are changing by 1-3% per year. These rates are too small to be measured by soil sampling. The weathering rate at Sogndal has been calculated to be in the range 10-20 meq/m^2/yr. Weathering cannot keep up with the increased leaching of base cations which accompany the new flux of sulphate in runoff.

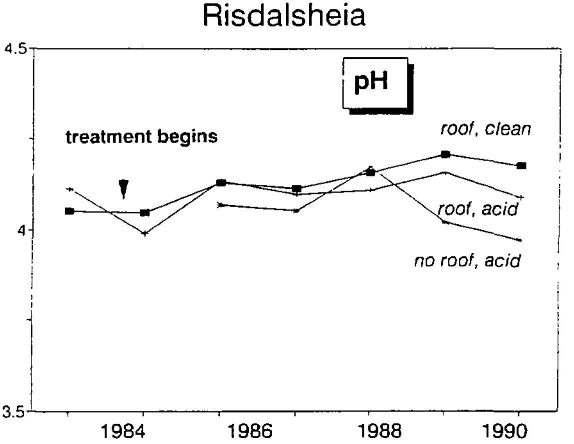


Figure 4:
At Risdalsheia pH has increased only slightly.

The RAIN data have been of great value for evaluating process-oriented hydro-chemical models since, this is the only manipulation project which works in both directions, to acidify and to deacidify, on complete catchment ecosystems. The MAGIC model has been calibrated to the data from both Sogndal and Risdalsheia, and the general trends predicted by the model agree reasonably well with the changes observed. The results from Risdalsheia have enabled an improvement of MAGIC by inclusion of a more accurate representation of organic acids.

Satellite projects

Several of the satellite projects have provided important information to the RAIN project (e.g. aluminum mobilization, chemical weathering) whilst in some cases the RAIN facilities have been important to the satellite projects through the existence of the experimental infrastructure (e.g. hydrological flowpaths, salt effect, acid episodes) and by providing data (e.g. modelling).

The satellite projects evolved on an opportunistic basis rather than from a scientific strategy. This was inevitable since funding constraints in the early stages of the project restricted the formal planning of a programme of supplementary field and laboratory work. Extra projects covering nutrient cycling, ecophysiology and turnover of organic matter would have been useful and perhaps should have been included in the main project from the outset.

The need for satellite projects to be self funding meant that international scientists were most successful in obtaining the necessary funds since national funding was directed at the basic data collection programme. Participation of other Norwegian institutes in satellite projects is small presumably as a result of too little funding and poor coordination of existing research activities.

All of the satellite projects have been reported, some in peer reviewed literature although in many cases this has been through conference proceedings and academic theses, and these are not easily available to the scientific community. If the satellite programme had been integrated as part of the main programme, this would have enabled the project manager to ensure adequate reporting and cooperation.

Contribution of the RAIN project to national and international research

The RAIN project was one of the first projects in the world to use the ecosystem approach for manipulation of the biogeochemical cycling of elements, apart from tree felling experiments and traditional liming and fertilizer trials. The project has been, and still is, an outstanding example of an application of the manipulation concept as a tool to obtain a better understanding of ecosystem function and dynamics.

Although experimental acidification projects have been launched at the same time at several places in different parts of the world, including Norway, the RAIN manipulation project was the first of its kind working on a catchment-scale. Similarly, the attempt at reversibility of acidification using roofed catchments was the first of its kind. Since then, the RAIN roof approach has become the model for several other experimental manipulation projects in Europe, and the applicability of the technique is still under development for other manipulation purposes and scientific goals.

The RAIN project has attracted many scientists, both national and especially international, to work at the two field sites. It is hoped that more researchers, especially with a more biological background (microbiologist, ecophysiologist, etc.), will participate in the future.

The results obtained from the RAIN project have been used in the development of mathematical models to predict future implications for nature protection according to potential legislative measures against emission of air pollutants.

The RAIN project has focused the attention of the scientific world (as well as funding agencies) on acid rain research as an important issue, and in this way it has helped the scientific community take a step forward in clarifying the effect of air pollution problems. During the last years, the results obtained have formed an important input to the assessment of critical loads for atmospheric inputs of sulphur and nitrogen compounds to ecosystems. In that context it is expected that results from the RAIN project will contribute further in the future, especially in the nitrogen assessment.

The publication of the main results of the RAIN project may inspire other researchers to start supplementary or satellite research projects at a higher level, without the need to create the basic data themselves. At the present stage of the project, more information is needed at the process level to open some of the "black boxes". Such detailed studies, performed by specialists, would greatly improve the scientific understanding of the whole acidification problem and must include nitrogen cycling and carbon cycling at Sogndal and Risdalsheia, respectively. This will enable further refinement of models by directly incorporating process equations based on observations at the sites.

We recognize the important links with the Humic lake acidification experiment (HUMEX) which may provide evidence to further explain the behaviour of organic acids in the runoff at the Risdalsheia site and we would support the need for future cooperation between these projects.

Significance of the RAIN project for environmental protection authorities

Besides being a significant scientific experiment giving clear and unequivocable results at Sogndal, RAIN has also been a powerful demonstration of air pollution impact on nature at Risdalsheia where the novel experimental approach of a roofed catchment and the rapid dissemination of results to a wide public, achieved through the popular press, may have contributed to political decisions. Repeated visits by UK politicians, environmental officials and industry representatives to this site are also thought to have played a role in the policy regarding emissions of sulphur and nitrogen oxides.

The RAIN site at Sogndal has not been used as extensively for demonstration purposes as the site at Risdalsheia, but the results of the experiments at Sogndal have clearly shown that acid rain can cause acidification of soil and streamwater.

The Norwegian environmental authorities have clearly stated the importance of the RAIN project, both in terms of its scientific findings and its high profile as a demonstration of the impacts of air pollution.

Publication and dissemination of results

The main results of the project have been reported in high profile scientific journals with a wide circulation, notably Nature. These papers are extremely well written and fully represent the scientific findings of the project.

The publication list presently totals twentyfour. Eight papers have appeared in scientific journals, four in conference proceedings and one in a popular science magazine. Ten institute reports and one thesis have been written.

Some detailed aspects of the work have not been written up due to lack of funding towards the end of the project. It should be possible to extract more publications from the data, notably describing seasonal fluctuations in water chemistry which may contain important signals with regard to carbon and nitrogen cycling. Further major publications are planned for 1991 to include the assessment of results through October 1991 at both Sogndal and Risdalsheia.

The high profile the project has been given in the popular press has ensured the widest possible platform for dissemination of results and may have served to heighten the impact of the project with policy makers.

The decision to give TEFA (*Tverrfaglig etatsgruppe for forsuringsspørsmål i Agderfylkene*) responsibility for site tours should be commended given the demands on the scientists and project managers' time and the need to inform a wider public.

Project economy

Table 1 explains the financial status of the RAIN project. It clearly shows that the project has received funding from several agencies. It is recognized that it must have taken a considerable amount of time to secure the funding at the level which has been obtained.

The high level of the costs has been due to a design which was necessarily expensive. In particular, inclusion of the second roof as an experimental control increased the expenses compared to the original budget plans.

Even though the project has been expensive, it has been cost effective. Concentration of many activities, including satellite studies within a few locations has given a high scientific output.

It is further recognized that NIVA played a crucial role in securing the RAIN project financially during the financial crisis in 1986, which arose mainly due to the high capital investments in the project. The crisis was overcome when NIVA took a bank loan, which was connected with a significant risk.

Table 1

	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1982-91
Expenses:											
Running	60	641	1625	1643	1844	1843	1971	2118	1943	815	14503
Capital	0	219	2607	332	10	50	10	81	50	0	3359
Rent Risdals.						300	300	300	300	300	1500
Total	60	860	4232	1975	1854	2193	2281	2499	2293	1115	19362
Income											
MD	50	215	425	200	200	650	780	725	800	900	4945
NTNF		0	150	450	450	475	400	300	300	0	2525
Ontario		965	117	302	315	338	496	172	[illegible]	0	2705
Env. Can.		0	610	372	488	288	137	144	75	0	2114
SNV		0	66	99	107	100	159	0	210	0	741
SWAP		0	450	0	0	0	0	0	0	0	450
CEGB/NatPower							861	669	1223	0	2753
Misc.		0	8	0	40	68	111	10	1	0	238
Subtotal	50	1180	1826	1423	1600	1919	2944	2020	2609	900	16471
NIVA		10	100	120	1700	250	280	320	305	165	3250
NILU		10	20	20	20	20	20	10	20	10	150
Total	50	1200	1946	1563	3320	2189	3244	2350	2934	1075	19871
Balance	-10	340	-2286	-412	1466	-4	963	-149	641	-40	509
Cum.Bal	-10	330	-1956	-2368	-902	-906	57	-92	549	509	509

The figures are given in 1000 NOK

Financial sources:

- **MD** Norwegian Ministry of Environment
- **NTNF** Royal Norwegian Council for Scientific and Industrial Research
- **Ontario** Ontario Ministry of the Environment
- **Env.Can.** Environment Canada
- **SNV** Swedish Environmental Protection Agency
- **SWAP** Surface Water Acidification Programme (The Royal Society, Norwegian Academy of Science and Letters, Royal Swedish Academy of Sciences)
- **CEGB** Central Electricity Generating Board (UK)
- **NatPower** National Power (UK)

Conducting institutes:

- **NIVA** Norwegian Institute for Water Research
- **NILU** Norwegian Institute for Air Research

Project Management

The success of the project is in no small way due to the enthusiasm and skills of the project manager. He has maintained a broad-minded approach in encouraging interdisciplinary satellite projects, making scientific and political contacts and securing continued funding from a range of national and international sponsors.

The management of the project has been hampered by a lack of resources to carry out more than just the basic monitoring programme and the problems of planning a comprehensive set of satellite experiments with less than desireable cooperation from other national groups and a lack of funds to employ qualified international groups.

The delegation of work and responsibilities by the project manager to staff members and satellite project scientists has created an inspiring and enthusiastic atmosphere within the framework of the RAIN project.

Future plans and recommendations

It is recommended that the RAIN project continues with the basic experimental manipulation programme, and that in the future more emphasis should be directed specifically at more detailed process studies. This can be achieved by extending the basic research programme and/or by the establishment of more satellite studies. If further satellite studies are initiated, the scientific design and personnel must be carefully selected in association with the basic programme. The existing studies on fish toxicity seem inadequate within the context of this manipulation study.

At Sogndal it is recommended that the project will be included in the European NITREX study aimed at establishment of critical loads for atmospheric nitrogen deposition. More information is needed at Sogndal on the internal nitrogen turnover, in the light of increased nitrogen leakage (Figure 5), and the links to the sulphur and carbon cycle. If possible such studies should be achieved by the use of the stable ^{15}N isotope. The sulphuric acid additions should also proceed, and the induced effects can be studied in parallel with the nitrogen studies. The effects on land and stream vegetation should be included in the experimental follow up, to get the appropriate biological answer on nitrogen loadings.

At Risdalsheia it is recommended that the ongoing roof experiments continue for another three year period. There are still unsolved problems regarding the slow recovery of the soil acidification (small increase in runoff pH and no or little recovery of base saturation), the effect of organic acid buffering (Figure 6) and the bleeding of sulphur from the organic or inorganic sulphur pool.

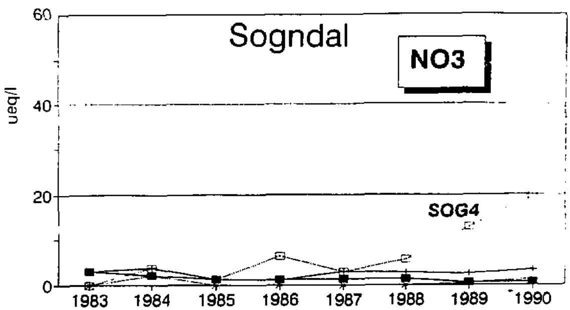


Figure 5:
Nitrogen has begun to leak from the catchment in Sogndal in the catchment where sulphate and nitrate has been added (SOG4).

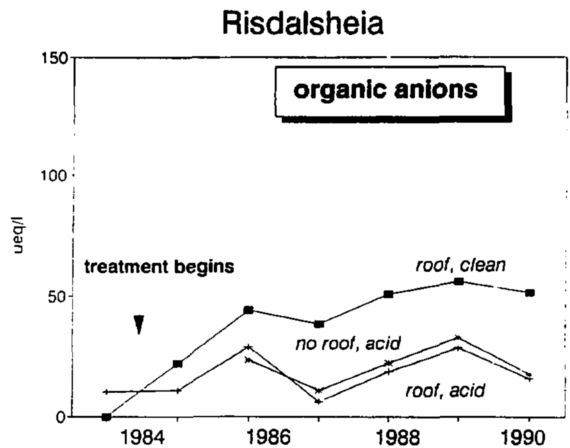


Figure 6:
At Risdalsheia the concentration of organic anions (determined from the ionic balance) have increased significantly in the roof-clean catchment relative to pre-treatment and relative to the controls.

After six years of experiments with the control roof (Egil), however, it can be concluded that the roof itself has no significant effect on the results. It is recommended, therefore, that the Egil roof may already be available for other experimental manipulation or for preparation of such experiments.

Studies on turnover of organic matter (the carbon cycle), and microbial and ecophysiological process studies should be established. As a minimum this could be done as laboratory experiments run in parallel with the field studies.

Having established expensive experimental field facilities (i.e. the roofs), they should also, if possible, be used for future research projects, and indeed plans are underway to undertake a CO_2 and temperature manipulation to assess the impact of climate change on catchment ecosystems (CLIMEX). The existence of the roofs and the experimental infrastructure and expertise at the site and at NIVA make such future manipulations both possible and attractive.

Final conclusions

In summary, the RAIN project is a scientifically sound and original project. The results have been of great significance both nationally and internationally and the experimental design has influenced many other initiatives on both national and international level. After eight years of research, big financial and manpower resources have been invested, but in a very cost-effective way. Many scientific results have been achieved and published, and the findings have formed a basis for political decisions and legislation. It is hoped that the project can be continued in the future, and that the recommendations for extensions of the project can be followed. Concentrating the common Norwegian research effort on large projects such as RAIN, can be the frame for an improvement of the total scientific level of the air pollution research and a more effective use of the available resources.

Norwegian Institute for Water Research

RAIN project 1983-91: highlights of research, dissemination of results, and plans for the future

A memorandum prepared for the evaluation conducted by
the Norwegian National Committee for Environmental Research

Richard F. Wright
manager, RAIN project

10 May 1991

Background

The Norwegian National Committee for Environmental Research (NMF) is conducting an evaluation of the RAIN project (Reversing Acidification In Norway). The evaluation is part of the mandate of NMF to coordinate research financed by the Norwegian Ministry of Environment, and to advise the Ministry with respect to planning and reviewing environmental research. This memorandum is prepared at the request of NMF to aid in the evaluation of the RAIN project.

Short history of the RAIN project

The RAIN project now approaches the formal end to its 8-year existence. The idea for the RAIN project was hatched in early 1981. The year 1982 was used to scotch out the project design, to select the sites, and to raise the necessary funds to carry out the research. The project began in full in June 1983 with treatment beginning in April 1984 at Sogndal and June 1984 at Risdalsheia. The original 5-year plan was extended for an additional three years, and the project formally ends June 1991, although there are plans to continue the experiment at Risdalsheia for a further 3 years, and at Sogndal through at least 1991.

The concept of the RAIN project grew out of the results of the 1980 Sandefjord conference. Sandefjord marked the end of the SNSF-project. The relationships between emissions of SO_2 and NO_x, long-range transport, deposition of acidifying compounds, acidification of lakes and rivers and loss of fish populations and damage to other aquatic organisms appeared to be quite well-established, at least empirically. The situation was similar in Europe and North America, with large emissions sources in major industrialized countries and remote, sensitive receptors in less-powerful countries. Most countries in both Europe and North America had agreed to reduce SO_2 emissions by 30% by the year 1993 relative to levels in 1980 (the "30% club" -- the Convention on Transboundary Air Pollutants under the United Nations Economic Commission for Europe).

Yet in 1980-81 there was very little information available regarding the reversibility of acidification of freshwaters. For decades emissions had been increasing, acid deposition had been increasing and spreading to new areas, and more and more lakes and rivers were experiencing damage to fish populations. The reductions in emissions were in part based on the assumption that such measures would ameliorate the acidification problems and protect the environment against further damage. But apart from "back-of-the-envelope" calculations and simple empirical models there was little hard evidence. To what extent is acidification reversible? How long will it take? Does recovery proceed along the same path as acidification, or are there lags and hysteresis? The RAIN project addressed these questions directly.

Because surface water acidification was the focus, it was recognized early on that catchment-scale manipulations were called for. Whole-ecosystem experiments had played an important role in environmental research during the late 1960's (the whole-catchment tree-felling experiment at Hubbard Brook Experimental Forest) and 1970's (the nutrient enrichment and acidification experiments at the Experimental Lakes Area). Whole-ecosystem experiments produced a wealth of new scientific information (both anticipated and unexpected), as well as providing superb environmental demonstrations.

Thus the concept of the RAIN project was conceived. The reversibility of acidification was to be examined directly by whole-catchment experiments in which the incoming acid deposition was excluded by means of a roof and clean rain applied beneath. In parallel a pristine catchment would be artificially acidified by addition of acid. This experiment would be technically simpler (and less expensive) in that no roof would be required. Together these manipulations would provide information regarding the rates of change following drastic change in acid deposition.

Clearly the roof experiment would be expensive and would entail major technical and scientific risks. It was apparent that creative financing was called for. Funding for such an enterprise would have to come from a variety of sources. The Canadians, in particular the Ontario Ministry of Environment, early on expressed interest in joining such a research project. The Canadians were also focussing on the issue of reversibility but did not have the resources at the time to carry out such an experiment alone. What then emerged in 1983 was the RAIN project, funded jointly for 5 years from Canadian and Norwegian sources, with a minor contribution from Sweden as well.

As the end of the 5-year period began to near, it became clear that only 4 years of treatment was too short a time to fully elucidate the changes in soils and runoff induced by the change in acid deposition. A 3-year extension was proposed. The Canadians were not able to continue funding at the previous high level, and instead this role was filled by the Central Electricity Generating Board (UK) (subsequently National Power). The RAIN project thus runs through June 1991 for a total of 8 years (1 year of background data and 7 years of treatment). Although the project then formally ends, there are plans to continue the experiment at Risdalsheia for a further 3 years, and at Sogndal through at least 1991.

Major research results

Runoff chemistry. At both Sogndal and Risdalsheia the change in acid deposition caused major changes in runoff chemistry. At Sogndal runoff was acidic with high concentrations of sulfate and aluminum already during the first snowmelt in spring 1984. Episodes of acidic, aluminum-rich runoff occurred after acid addition. A batch experiment with salmon fry showed that this water was toxic to fish. As the acid additions proceeded, runoff began to show signs of chronic acidification. Sulfate concentrations increased from year-to-year; this increase was accompanied by an increase in base cation concentrations and decreases in alkalinity and pH.

At Sogndal for the first several years of treatment nitrate concentrations in runoff remained low with the exception of the few hours to days immediately following the application of nitric acid to catchment SOG4, and during the first phases of snowmelt at all catchments. But in 1989 the signs of "nitrogen saturation" appeared at catchment SOG4. Nitrate concentrations remained significantly high for several weeks following the last application of acid in October. This continued in 1990. But the real surprise came at catchment SOG2, which receives only sulfuric acid. Here in 1990 nitrate concentrations s in runoff were above background levels for much of the summer and autumn. Seven years of acidification by sulfuric acid had apparently disrupted the nitrogen cycle in the terrestrial catchment to the extent that nitrate was leached in runoff. With the current increasing attention to the role of nitrogen in acidification, the nitrogen results from Sogndal are of great interest. For this reason Sogndal is proposed as a Norwegian site for the European NITREX project (Nitrogen Saturation Experiments).

At Risdalsheia acid exclusion resulted in almost immediate decrease in nitrate and ammonium concentrations in runoff. (That nitrate responds rapidly to changes in deposition was further illustrated in autumn 1984 when a technical failure of the ion-exchange columns resulted in the accidental application of nitric acid rain beneath the roof; nitrate concentrations in runoff went up immediately and then decreased again after the system was repaired.) Sulfate concentrations began to decrease late 1984 and have continued to decrease in subsequent years. The decline in strong acid anion concentrations has been compensated by a decline in concentrations of base cations and by an increase in alkalinity.

pH levels at Risdalsheia have not shown the expected major increase, however. Dissociation of organic acids has buffered against pH change in the highly-colored runoff.

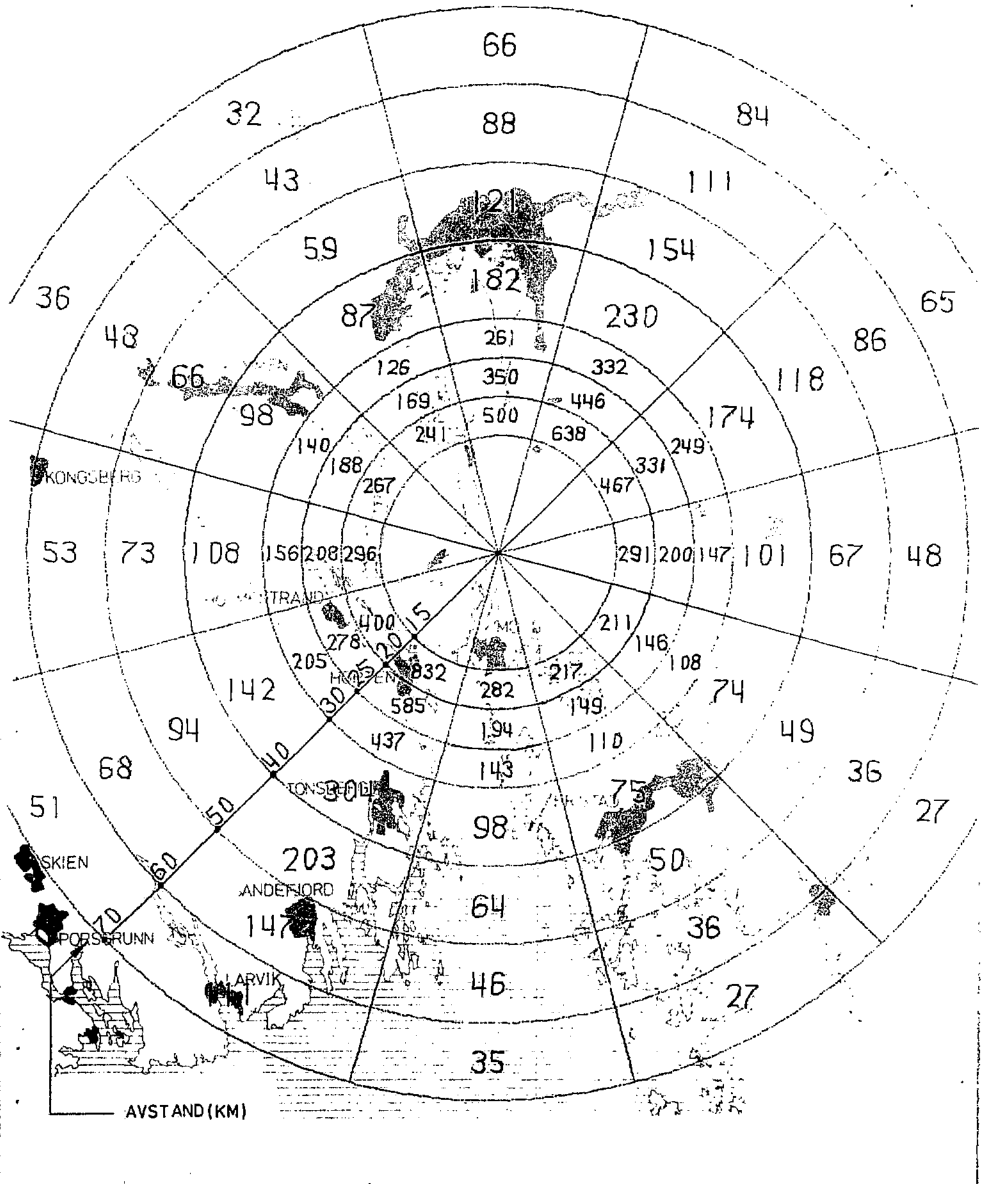
Experiments on site show that the runoff is still toxic to fish; pH is too low, calcium is too low, and labile aluminum is too high. Additional years of treatment are necessary to fully evaluate the role of organic acids, the expected increase in pH, and the toxicity to fish.

The pH levels and concentrations of labile aluminum in runoff at Sogndal suggested the presence of a highly-soluble aluminum hydroxide phase with apparent log solubility product of about 9.1 in 1984 but decreasing to about 8.1 in subsequent years. At Risdalsheia aluminum is apparently much less soluble; here the pH-Al relationship indicates an aluminum hydroxide phase with log solubility product of only 6.7.

Soils. The trends in sulfate concentrations and fluxes at both Sogndal and Risdalsheia indicate that the soils have a significant but limited capacity to retain and release sulfate and thus regulate concentrations of sulfate in runoff. The soil surveys conducted 1984-86 indicate that the treatments have changed the amounts of water-soluble and adsorbed sulfate in the soils. Sulfate adsorption as described by Langmuir-type isotherms roughly account for the observed trends.

The pool of exchangeable base cations in the soils is also changing at both Risdalsheia and Sogndal. Input-output budgets indicate that the pool sizes are changing by 1-3% per year. These rates are as yet too small to be measured in the soil surveys, but after >10 years of treatment the changes should be measurable in the field. Acidification of soils is commonly defined as change in base saturation, and by this measure the treatment at Sogndal has acidified the soil, whereas at Risdalsheia the soils have begun to recover.

Soils at both Sogndal and Risdalsheia are sensitive to acidification. The soils are thin and patchy and derived from parent material dominated by minerals highly resistant to chemical weathering. Weathering rate at Sogndal is only 10-20 meq/m^2/yr (sum of base cations). Acid addition has caused at most only a small increase in the weathering rate. Thus the release of base cations through weathering cannot keep up with the increased leaching of base cations which accompany the new flux of sulfate in runoff. The result is a depletion in the pool of exchangeable base cations -- soil acidification.



MØRK. PWR. 150M SKORSTEIN. INDIVIDUELL DOSE. (ENHET 10^{6} MREM/ÅR) FIGUR 4.12

Soil Sciences, Swedish University of Agricultural Sciences (SLU). Due to various reasons both SI and NVE dropped out in the first years of the project.

Active participants and their principal tasks have been:

At NIVA

scientists

T. Frogner, chemistry Sogndal, 87-90

E. Gjessing, project manager 83-84, Sogndal 83-91

F. Kroglund, fish Risdalsheia, 88-91

R. Storhaug, sprinkling systems 83-84

K. Wedum, roof construction 83-84

R. Wright, project manager, reporting, water chemistry 84-91

assistants

S. Andersen, applications Sogndal 83-91

H. Efraimsen, applications Sogndal 85-88

M.B. Flaten, data management 87-90

B. Hals, discharge Sogndal 87-91

R. Høgberget, site manager Risdalsheia 83-91

M. Lie, applications Risdalsheia 88-91

T. Mindrebø, applications Risdalsheia 86-88

T.J. Oredalen, data management 90-91

A. Rogne, data management 83-90

At NILU

scientist

A. Semb, precipitation 83-91

At SLU

scientists

E. Lotse, soils 83-88

J. Erikson, soils 90

assistant

E. Ottabong, soils 83-86

At SI

scientists

N. Christophersen, models 83-85

H.M. Seip, models 83-85

At NVE

scientist

B. Sletaune, discharge Sogndal 83-86

M.S. and Ph.D. students associated with the RAIN project

There have been several post-doctoral fellows and students associated with the RAIN project either directly or indirectly.

Postdoctoral level:

Michael Hauhs (Dr. philos. Univ. Göttingen 1986) Subject: hydrological flowpaths Risdalsheia

Ph.D. level:

Tore Frogner (dr. scient. 1990 Univ. Oslo) Subject: chemical weathering at Sogndal

Elin Gjengedal (dr. scient. in progress Univ. Trondheim) Subject: heavy metals in plants and soils

M.S. level:

Dorothy Bergmann (M.S. 1991 Northern Arizona Univ. USA) Subject: Aluminum mobilization in soils at Risdalsheia

Rita Hansen (cand. scient. 1991 Univ. Oslo) Subject: organic acids

Terry Tinl (M.S. 1986 Norterhn Arizona Univ. USA) Subject: Aluminum mobilization in soils at Sogndal

Satellite projects

The RAIN project created an experimental base upon which related studies can build. From the start various research groups expressed interest in using the RAIN sites to study aspects not included in the original design. These satellite projects have been conducted with funding obtained independently of the RAIN project, although in many cases the work was coordinated and assisted by RAIN project personnel if possible. The satellite projects include:

1. Trace metals in vegetation at Risdalsheia and Sogndal. E. Steinnes, principal investigator, University of Trondheim. Funding from Norwegian and Swedish sources. Publication: Gjengedal, E. and Steinnes, E. 1989. Impact of soil acidification on the mobility of metals in the soil-plant system. In: Vol. 2 Proc. Heavy Metals in the Environment Conf. Geneva, 12-15 September 1989, p. 40-43.

2. Aluminum mobilization in soils at Risdalsheia and Sogndal. R.A. Parnell, principal investigator, Northern Arizona University, USA. Funding from EPRI (USA) and National Geographic Society (USA). Publications: Tinl, T. 1986. Aluminum mobility in soils at Sogndal. M.Sc. Thesis, Northern Arizona University, USA. Bergmann, D. in prep. Aluminum mobility in soils at Risdalsheia. M.Sc. Thesis, Northern Arizona University, USA.

3. Historical weathering rates at Risdalsheia and Sogndal. E. Lotse, principal investigator. Swedish Agricultural University. Funding from Surface Water Acidification Programme (SWAP). Publication: Lotse, E. 1989. Soil chemistry 1983-86 at the RAIN project catchments. Acid Rain Research Report 18/1989 (Norwegian Institute for Water Research, Oslo), 66 pp.

4. Chemical weathering at Sogndal. T. Frogner, principal investigator. Funding from Surface Water Acidification Programme (SWAP) and NTNF (Norway). Publication: Frogner, T. 1990. The effect of acid deposition on cation fluxes in artificially acidified catchments in Western Norway. Geochim. Cosmochim. Acta. 54: 769-780.

5. Modelling reversibility of acidification. R. Wright, principal investigator. Funding from Surface Water Acidification Programme (SWAP) and NIVA. Publications: Wright, R.F. and B. J. Cosby, 1987. Use of a process-oriented model to predict

acidification at manipulated catchments in Norway. Atmos. Environ. 21: 727-730. Wright, R.F., Cosby, B.J., Flaten, M.B., and Reuss, J.O. 1990. Evaluation of an acidification model with data from manipulated catchments in Norway. Nature, 343: 53-55.

6. Hydrologic flowpaths in the unsaturated zone: Risdalsheia. M. Hauhs, principal investigator. Funding from NTNF, Norwegian Hydrologic Committee (NHK) and NIVA. Publications: Hauhs, M. 1986. Relation between chemistry of soil solution and runoff in two contrasting watersheds: Lange Bramke (West Germany) and Risdalsheia (Norway), p. 207-217, In S. Haldorsen and E.J. Berntsen (eds.) Water in the Unsaturated Zone (Nordic Hydrologic Programme Report 15, P.O. Box 5091, 0301 Oslo), 284 pp. Hauhs, M. 1987. The relation between water flow paths in the soil and runoff chemistry at Risdalsheia, a small headwater catchment in southern Norway (RAIN-project), p. 173-184, In Acidification and Water Pathways, vol. I. (Norwegian National Committee for Hydrology, P.O.Box 5091, 0301 Oslo 3), 458 pp. Hauhs, M. 1988. Water and ion movement through a minicatchment at Risdalsheia, Norway (RAIN project). Acid Rain Res. Rept. 14/88 (Norwegian Inst. Water Research, Oslo, Norway), 74pp.

7. "Sea-salt effect" at Sogndal. S.A. Norton, principal investigator. Funding from NTNF and NIVA. Publication: Wright, R.F., Norton, S.A., Brakke, D.F and Frogner, T. 1988. Experimental verification of episodic acidification of freshwaters by seasalts. Nature 334: 422-424.

8. Buffering effect of streambed at Sogndal. S.A. Norton, principal investigator. Funding from NTNF and NIVA. Publication: Frogner, T., Wright, R.F., and Norton, S.A. in prep. Experimental acid addition to soils and streams at Sogndal, western Norway: short- and long-term effects on aluminum solubility. (Included as part of Frogner, T. 1990 Ph.D. Thesis, University of Oslo).

9. Organic acids in runoff at Risdalsheia. R.V. Hansen, principal investigator. Funding from Univ. Oslo and NIVA. Publication: Hansen, R.V. 1991. Bufferkapasitet,

sterke og svake syrer i naturlig vann. Cand. scient. Thesis, University of Oslo (in Norwegian).

10. Pigments in mosses as environmental indicator. A. Løken, principal investigator. Norwegian Technical University, Trondheim. Publication: Løken, A. 1990. Terrestrisk overvåking - moser. En kjemisk analyse. Report. 39pp. (in Norwegian).

11. Fish studies in conjunction with project RAIN. F. Kroglund, principal investigator, NIVA. Funding from CEGB (UK), National Power (UK) and NIVA.

12. Terrestrial insects and consequences for birds: Sogndal. S.J. Ormerod, principal investigator. National Rivers Authority, Wales, UK. Funding from The Royal Society of Chemistry (UK). Publication: Rundle, S.D. and Ormerod, S.J. in review. The influence of artificial acid deposition on the quantity and quality of terrestrial arthropods in sub-arctic heathland, and possible consequences for birds. *Environ. Pollut.*

Contribution to Norwegian and international acid rain research

It is difficult to assess the impact of a single research project such as the RAIN project on Norwegian and international acid rain research. The RAIN project has produced many scientific reports and publications. Copies and reprints of reports and articles are commonly requested by about 200-300 individuals. Several of the key articles have been published in leading scientific journals such as Nature. The article describing the results from the first year of treatment (presented at Muskoka '85 and published 1986 in Water Air Soil Pollut.) has been cited 10 times (search in Science Citation Index), and the major article describing 4 years of treatment (published in 1988 in Nature) has already been cited 17 times (and not only by the authors themselves in subsequent articles!). The 1988 Nature article attracted much interest and in fact was treated as a news article by newspapers, radio and television in several countries in Europe and North America.

The RAIN project has had a prominent position at major acid rain conferences. It was the subject of a plenary lecture at Muskoka '85 and part of a plenary lecture at Glasgow '90.

The RAIN project has focussed attention in the international research community on the issue of reversibility of acidification. A workshop organized jointly by the Commission of European Communities (CEC) and the Royal Norwegian Council for Scientific and Industrial Research (NTNF) on reversibility was held June 1986 in Grimstad; the location was chosen because of the proximity to Risdalsheia. The proceedings of the workshop are published (Barth, H. (ed.) 1987 Reversibility of Acidification. Elsevier Applied Science, London, 175pp.).

The success of the roofed catchments at Risdalsheia has undoubtedly encouraged similar large-scale exclosures elsewhere. This approach is now used in the Netherlands, Denmark, Germany and Sweden. The large-scale acid addition experiments at Sogndal have also influenced research elsewhere. At the Watershed Manipulation Project in Maine, USA, a similar (but 30 times larger) catchment scale manipulation is now underway, and many of the features were modelled after the Sogndal experiment.

Finances

The RAIN project cost about 20 million NOK over the entire 8-year period 1983-91 (Table 1). Of this about 3.4 million is capital investment (mostly at Risdalsheia) and the remainder is running expense (of which about 2/3 goes to personnel costs). The annual level of effort has been about 4 man-years.

Research funds for the RAIN project have come from 9 major sources (Table 1). Roughly 55% of the funding has been from Norwegian sources (25% from MD, 13% from NTNF and 17% from the participating institutes NIVA and NILU), and the remaining 45% from Canada (24%), the UK (16%), and Sweden (4%) (Figure 1).

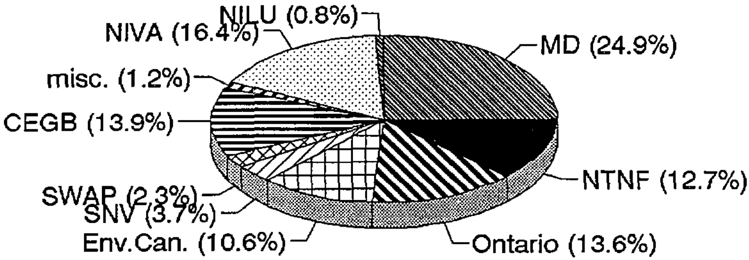
Financing and managing a research project as complex and technically risky as the RAIN project has not been an easy task. The original research proposal of 1983 turned out to

RAIN PROJECT FINANCIAL STATUS 30-Apr-91

UNIT 1000 NOK

	1982	1983	1984	1985	1986	1987	1988	1989	1990	budget 1/2 1991	Total 1982-91
Expenses											
running	60	641	1625	1643	1844	1843	1971	2118	1943	815	14503
capital	0	219	2607	332	10	50	10	81	50	0	3359
rent Risd						300	300	300	300	300	1500
total	60	860	4232	1975	1854	2193	2281	2499	2293	1115	19362
Income											
MD	50	215	425	200	200	650	780	725	800	900	4945
NTNF		0	150	450	450	475	400	300	300	0	2525
Ontario		965	117	302	315	338	496	172	0	0	2705
Env.Can.		0	610	372	488	288	137	144	75	0	2114
SNV		0	66	99	107	100	159	0	210	0	741
SWAP		0	450	0	0	0	0	0	0	0	450
CEGB/NatPower							861	669	1223	0	2753
misc.		0	8	0	40	68	111	10	1	0	238
subtotal	50	1180	1826	1423	1600	1919	2944	2020	2609	900	16471
NIVA		10	100	120	1700	250	280	320	305	165	3250
NILU		10	20	20	20	20	20	10	20	10	150
total	50	1200	1946	1563	3320	2189	3244	2350	2934	1075	19871
Balance	-10	340	-2286	-412	1466	-4	963	-149	641	-40	509
Cum.Bal.	-10	330	-1956	-2368	-902	-906	57	-92	549	509	509

RAIN project 1982-90
income 1000 NOK



total 19871 NOK

severely underestimate the construction costs at Risdalsheia. Also the original plan to build only one roof was changed after the initial research grants were obtained to encompass not one but two roofs at Risdalsheia. As a result the RAIN project was seriously underfunded from the beginning (Table 1).

By the end of 1984 the RAIN project was in serious financial trouble. The project was in the red by nearly 2 million NOK. NIVA had advanced the project this sum from the institute's liquid assets, but clearly could not be expected to continue to do so. NIVA took out a 3-year bank loan for 1.5 million NOK on behalf of the RAIN project; interest was charged to the project, and the capital was to be paid back to NIVA over a 5-year period starting in 1987 (charged as rent Risdalsheia in the budget). Without this support from NIVA the RAIN project would have had to close down already in 1985.

A 3-year extension of the RAIN project from June 1988-June 1991 was agreed in principle already in 1986. Here the intention was not only to enhance the scientific content, but also to obtain fresh funding to help make up the financial deficit. Both MD and NTNF entered the agreement with NIVA to provide 50% funding for the extension, and NIVA then entered a contract with CEGB (later National Power) for the other 50% funding. The Swedish Environmental Protection Board (SNV) also agreed to continue financing at about the same level as previously. The Swedish funds were earmarked for work with nitrogen at Sogndal.

As the RAIN project now near its official close in June 1991, the budget is in good shape, and there are sufficient funds which can be used to pay for closing down and cleaning up at both sites when that time comes.

Relevance for environmental authorities

Large-scale controlled whole-ecosystem experiments play an increasingly important role in environmental research. Such experiments are a powerful research tool, but also as environmental demonstrations that become central in forming national and international environmental policy. There is nothing better than a well-designed and executed whole-ecosystem experiment to convince skeptical scientists and environmental policy-makers of the role of specific pollutants in causing environmental change. Although the RAIN project is first and foremost a research project, it has had great value as an environmental demonstration. Repeated visits by UK politicians, environmental officials and industry representatives to the RAIN site at Risdalsheia are thought to have played a key role in the 1987 official British change in policy regarding emissions of sulfur and nitrogen oxides.

The RAIN project has also comprised part of the Canadian national research program on acid deposition and its environmental effects. The results from the RAIN project have thus augmented North American research, especially with respect to the important issue of reversibility.

Popular science: information to the public

The RAIN project provides a large-scale demonstration of the role of acid deposition in the acidification of freshwaters (Sogndal) and the fact that reduction in acid deposition will restore acidified freshwaters (Risdalsheia). It soon became apparent that the exclosures at Risdalsheia were of enormous interest to politician, environmental authorities, scientist, environmental interest groups, school groups of all ages, and the general public. Each year 300-1000 visitors find their way to Risdalsheia (Appendix 1), despite the facts that is far from the nearest city, difficult to find, and accessible only via a private road with locked gate.

The RAIN project was designed and set up as a basic research project. Its utility as an environmental demonstration is a by-product. While it is always flattering to receive attention and to feel that one's research is of interest and environmental relevance, it soon became apparent that the frequent visitors were too much of a good thing. A larger and larger fraction of the scientists' time was being filled with escorting visitors to Risdalsheia. In 1986 with the financial support of the Ministry of Environment, NIVA entered into a cooperative agreement with the "Interdisciplinary governmental group for acidification questions in the counties of East- and West-Agder" (TEFA Tverrfaglig Etatsgruppe for Forsuringsspørsmål i Agder-fylkene", Tomas-Andre Eid, secretary). TEFA began to use the RAIN project as part of their information activities in the region, and at the same time took responsibility to guide school groups etc. on visits to the site. Together a brochure suitable for the general public was produced. This cooperation has proven to be quite successful and satisfactory for all parties.

The visual impact of the roofed catchments and the sheer audacity of even conducting such an experiment has attracted film and TV crews, newspaper reporters, and science writers from several countries in Europe and North America. The RAIN project has figured in TV programs in Norway, Sweden, Denmark, Germany, UK, Canada and the USA. It has been described in articles in popular scientific magazines such as Geo, and Science News, has appeared on the cover of Nature in conjunction with an article on Nordic science, and has been reported as news in newspapers in Europe and North America such as The Times (London), and The Boston Globe (USA).

Within Norway the RAIN project has received extensive coverage on Norwegian TV and radio as well as in local and national newspapers (Appendix 2). And for good or for worse a whole new generation of Norwegians will learn about the RAIN project; a 2-page description is included in the standard science textbook for the 7th grade.

Plans for the future

The RAIN project formally finishes in June 1991, but there are concrete plans to continue research at both Sogndal and Risdalsheia. At Sogndal the increased leakage of nitrate from both catchments SOG4 (H_2SO_4 + HNO_3) and especially SOG2 (H_2SO_4) is of great interest with respect to the role of nitrogen in acidification of soils and surface waters. The treatments at Sogndal will be continued though 1991 with funding from NIVA to complete the hydrologic year. Sogndal is currently set up as the Norwegian site in NITREX (Nitrogen saturation experiments), a large international project partly funded by the Commission of European Communities (STEP).

Beyond 1991 the funding and hence fate for Sogndal is uncertain. There is not room in the current budget for NITREX for funding continued treatment at Sogndal. At the current level of scientific effort, running costs at Sogndal amounts to about 900 000 NOK annually, a sum which includes treatment, chemical analyses and reporting. A proposal for funding at this level to continue treatment at Sogndal for an additional 3-years (1992, 1993 and 1994) will be made to NMF (NAVF).

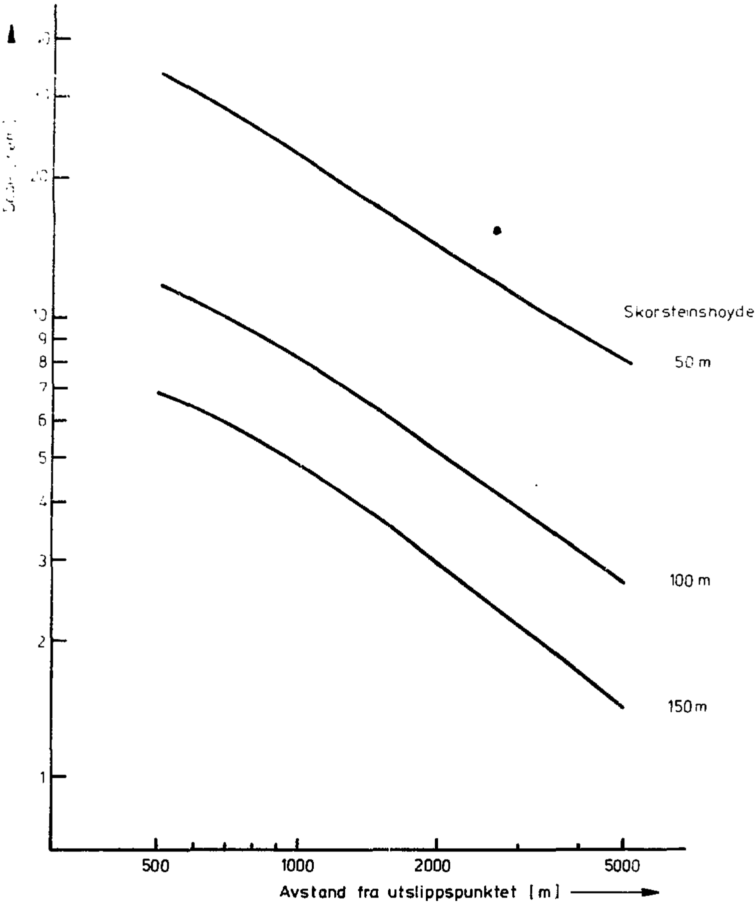
In the event that funding for continued treatment is not forthcoming, treatment at Sogndal will cease with the last application in October 1991, and 1992 will simply be a follow-up year with regular water sampling to document the return towards preacidification conditions. The cost for conducting this follow-up work is about 400 000 NOK, which includes sampling, analyses and reporting. In this case the site will be closed down completely November 1992.

Future plans for Risdalsheia are more extensive. A further 3-year continuation of the current experiment from June 1991 to June 1994 is now planned with 50% funding from the UK (remaining funds from SWAP) and 50% funding from NMF (NAVF). For the latter a formal proposal will be submitted 1 June 1991 for financing to begin January 1992. Costs for continuation of the Risdalsheia experiment are estimated at about 1.3 million NOK annually. Here the major objective is to clarify the role of organic acids in the response of runoff to the decreased acid deposition.

There are also concrete long-term plans for Risdalsheia. This unique environmental facility is well-suited for a whole-ecosystem experiments to simulate effects of future climate change on vegetation, soils and runoff. CLIMEX (Climate change experiment) is a proposed international, interdisciplinary research project in which the air temperature and CO_2 content will be increased to simulate a future scenario of climate change and the effects at the ecosystem scale. Such ecosystem scale experiments have been given high research priority by a number of international organizations. And the boreal forest is emerging as one of the biomes of greatest interest. CLIMEX will also be designed to measure the feedback to the atmosphere: the ecosystem change caused by climate change could result in changes in release of greenhouse gases from the soils.

CLIMEX is currently at the planning stage. A number of possible funding sources have been approached. The plans now entail making detailed proposals for funding to various organizations including national environmental authorities in the participating countries, the Commission of European Communities, and several organizations in Canada and the United States. At the moment a modest grant to cover planning has been received from the Ontario Ministry of Environment.

Plans for CLIMEX should not conflict with the 3-year continuation of the RAIN experiment at Risdalsheia. CLIMEX will require at least one full year of background



Skjoldbruskkjerteldose, voksne, 0-30 dögn.
Dimensjonerende uhell etter 1. sett forutsetninger.
Trykkvannsreaktor.

FIGUR 4.20

Barth (ed.) Reversibility of Acidification (Elsevier Applied Science, London), 175pp.

9. Hauhs, M. 1986. Relation between chemistry of soil solution and runoff in two contrasting watersheds: Lange Bramke (West Germany) and Risdalsheia (Norway), p. 207-217, In S. Haldorsen and E.J. Berntsen (eds.) Water in the Unsaturated Zone (Nordic Hydrologic Programme Report 15, P.O. Box 5091, 0301 Oslo), 284 pp.

10. Hauhs, M. 1987. The relation between water flow paths in the soil and runoff chemistry at Risdalsheia, a small headwater catchment in southern Norway (RAIN-project), p. 173-184, In Acidification and Water Pathways, vol. I. (Norwegian National Committee for Hydrology, P.O.Box 5091, 0301 Oslo 3), 458 pp.

11. Wright, R.F., 1987. RAIN project. Annual report for 1986. Acid Rain Res. Rept. 13/87 (Norwegian Inst. Water Research, Oslo, Norway), 90pp.

12. Parmann, G. 1988. Det nytter å redusere sur nedbør. Populærvitenskapelig Magasin 3/88: 8-11 (in Norwegian).

13. Hauhs, M. 1988. Water and ion movement through a minicatchment at Risdalsheia, Norway (RAIN project). Acid Rain Res. Rept. 14/88 (Norwegian Inst. Water Research, Oslo, Norway), 74pp.

14. Wright, R.F., 1988. RAIN project. Annual report for 1987. Acid Rain Res. Rept. 16/88 (Norwegian Inst. Water Research, Oslo, Norway), 77pp.

15. Wright, R.F., Norton, S.A., Brakke, D.F and Frogner, T. 1988. Experimental verification of episodic acidification of freshwaters by seasalts. Nature 334: 422-424.

16. Wright, R.F., Lotse, E., and Semb, A. 1988. Reversibility of acidification shown by whole-catchment experiments. Nature 334: 670-675.

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18. Lotse, E. 1989. Soil chemistry 1983-86 at the RAIN project catchments. Acid Rain Research Report 18/1989 (Norwegian Institute for Water Research, Oslo), 66 pp.

19. Reuss, J.O. 1989. Interpretation of soil data from the RAIN project. Acid Rain Research Report 19/1989 (Norwegian Institute for Water Research, Oslo), 81 pp.

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22. Wright, R.F., and Henriksen, A. 1990. The RAIN project - an overview, p. 161-166, In B.J. Mason (ed.) The Surface Waters Acidification Programme (Cambridge University Press, Cambridge), 522 pp.

23. Hansen, R.V. 1991. Bufferkapasitet, sterke og svake syrer i naturlig vann. Cand. scient. Thesis, University of Oslo (in Norwegian).

24. Wright, R.F. in press. RAIN project. Annual report for 1988, 1989 and 1990. Acid Rain Research Report 24/91 (Norwegian Institute for Water Research, Oslo, Norway).

The Norwegian National Committee for Environmental Research (NMF) promotes cooperation between the Norwegian research council in order to coordinate national efforts in the field of environmental research. In particular, the Committee gives advice on and coordinates research which is funded by the Ministry of Environment.

Nasjonal komité for miljøvernforskning

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