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CRITICAL LOADS INTEGRATED MONITORING PROGRAMME AND DEVELOPMENT OF DYNAMIC MODELS

Final Summary Report

Under contract to DETR (EPG1/3/84)

September 1998

Contents

1. Overall project aim

The aim of this contract was to develop and calibrate dynamic models using detailed monitoring data from two sites and apply the models to other UK and European catchments under different future sulphur and nitrogen deposition scenarios. The contract fulfils the UK commitment to the UNECE ICP-IM and provides UK input to the international need for research on model development.

2. Background

Sensitive parts of the United Kingdom have undergone damage through acidic deposition. This was recognised and recently the United Kingdom signed the Oslo Protocol (within the Convention on Long Range Transboundary Air Pollution of the United Nations Economic Commission, UNECE-CLRTAP) and is committed to reducing emissions of sulphur dioxide by 80% in 2010 relative to emissions in 1980. Acidification can also be caused by emissions of nitrogen compounds such as NOx and ammonia. Deliberations on a second Nitrogen protocol within the UNECE have now commenced.

The UK has argued for effects based control strategies based on critical loads - a level of deposition below which damage does not occur. These are mapped throughout Europe so that effort can be focused on those areas which are at the greatest environmental risk ensuring the most cost effective control strategy is implemented. Critical loads maps show which areas are most at risk from acidification at present but give no indication about how the ecosystem will respond through time to continued acidifying inputs. It is important to be able to predict the behaviour of sensitive ecosystems to present and future loadings of acidifying pollutants so as to allow as assessment of the timescales over which any emissions reductions might be undertaken. Choice of timescale is important both from the point of view of limiting damage to sensitive ecosystems and also from the point of view of not placing an unrealistic financial burden on industry.

One way to predict ecosystem response to varying pollutant loadings is via dynamic modelling. Dynamic models have been developed for sulphur but the behaviour of nitrogen in soils and fresh waters is much more complex and a need for further model development and validation incorporating both nitrogen and sulphur is required for policy development purposes.

The International Co-operative Programme on Integrated Monitoring (ICP IM) was established as a permanent programme, under the UNECE LRTAP in 1993. The main aim is to determine and predict the state of ecosystems/catchments and their changes in a long-term perspective, with respect to the regional variation and impact of air pollutants, especially Nitrogen and Sulphur. Such intensive monitoring of sites is essential in order to generate the data which dynamic models require in order to function.

3. Summary of Research Results

Research results can be summarised under three broad headings: data summary and assessment from UK ICP-IM sites, assessment of sulphur reduction scenarios using MAGIC and MAGIC model development to include N dynamics.

(i) Data trends at UK ICP-IM sites

The contrast in stream chemistry between the sites reflects the respective pollutant load to each IM catchment. The stream waters of the Afon Hafren are highly acidic in contrast to the Allt a'Mharcaidh where they are relatively well buffered. The chemistry at both sites show regular seasonal variations. Storm flow during the winter months is derived from organic upper soil layers, flushing SO_4, NO_3 and DOC and causing episodic acidification. During periods of low flow, well buffered groundwater and deep soil water feed each stream; this is reflected by higher base cation concentrations.

The only significant long term trend in stream chemistry is an increase in DOC, evident at both sites. This may be related to the erosion of peat soils and subsequent organic matter breakdown. The cause of the increase remains unclear although climatic variation may be of significance. Stream NO_3 concentrations at the Afon Hafren appear to have increased in recent years. This may be explained by a number of small felling operations since 1995 which cause the release of NO_3-N. In addition, precipitation-weighted annual mean NO_3 indicates a slight increase in catchment input, above the long term mean, in 1995-1997. However, interpretation of the NO_3 trend must be undertaken with care as biomass retention of N causes a marked seasonal cycle.

(ii) Assessment of Sulphur Reduction Scenarios

Predictions of soil and surface water at the UKAWMN sites in response to the EU Acidification Strategy B1 scenarios have been assessed. This scenario identifies for the year 2010, the cost-minimal allocation of emission reductions to attain in each grid cell within the EU a decrease of the area of unprotected ecosystems by at least 50 per cent (ie closing the gap of unprotected ecosystems by 50 per cent). The deposition reductions predicted by HARM for the UKAWMN sites from this emission scenario represent a reduction of between 72% and 90% of present day deposition and are significantly larger reductions than predicted by HARM under the Oslo Protocol .

The calibrated MAGIC model for 21 of the UKAWMN sites has been used to predict the acidification of soil and water in response to the B1 emissions reduction scenario. The corresponding S and N deposition is assumed to begin immediately and decrease linearly, to the target level set by the B1 scenario, by 2010 and then to continue at that level to 2050. At all sites a recovery from present day level of ANC is predicted. The longer term re-acidification predicted at some sites under the Oslo Protocol scenario is not predicted at any site indicating that the deposition under the B1 emissions scenario is below the critical load at all sites. By 2040, the model also predicts the recovery in pH at all sites which is significantly greater than that predicted under the Oslo Protocol. In addition, under the B1 scenario, the decline in soil base saturation in the future is halted at almost all sites and significant recovery is predicted at some sites. A crucial question which remains unaddressed is the biological significance of the water chemistry recovery under the B1 scenario relative to that under the Oslo Protocol. The cost/benefit implications of the higher level of emission reductions could be assessed from an approach of this type, combining hydrochemical and biological response modelling.

In addition to international agreement over the amount of emission reduction, the soil and water recovery in time is directly related to the timing of the agreed emission reductions. In this respect, existing (Oslo Protocol) and planned (EU acidification strategy) agreements focus on 2010 for the achievement of the emission targets. The implications of delaying this target has been assessed at the UKAWMN sites.

The net effect of extending the target year beyond 2010 is to increase the S deposition flux to each site over the forecast period. As a result, the predictions of surface water ANC recovery are delayed in response to the later target year. This delay is most evident at the more acidic (low ANC) sites. In the longer term or at least by 2050, however, the choice of target year is unimportant and all three scenarios achieve the same recovery. This result emphasises that the recovery as a result of deposition reduction will be rapid and in the longer-term, the size of emission reduction is more important than the timing of the reduction. This rapid response to changes in S deposition is in part due to the assumption of low S adsorption at UK sites. If S adsorption in catchment soils is significant at these sites then the dynamic response documented here represents an over-optimistic recovery in the short-term. Again, this analysis needs to be combined with biological response modelling and could be coupled with cost/benefit assessment.

The key conclusions are:

(i) The S emission reductions under the B1 scenario are predicted to lead to long-term surface water ANC recovery at all sites. This assumes no future change in the current level of net ecosystem retention of N or in the deposition flux of total N.

(ii) The predicted recovery in surface water ANC under the B1 scenario is greater than under the Oslo Protocol and is sustained at all sites. The predicted re-acidification at some of the more acidified sites under the Oslo Protocol S emission reductions does not occur under the B1 scenario. This emphasises that surface water critical load for total acidity at all sites is achieved by the B1 emissions reduction scenario. (NB. The N assumptions detailed above are critical to this conclusion).

(iii) Over the 30 to 50 year timescale, the size of the S emission reduction determines the degree of recovery in surface water ANC.

(iv) Over a shorter timescale, up to 30 years, the timing of the S emission reductions determines the rate of recovery. The quicker the target level of reductions is achieved, the more rapid the surface water ANC recovery. This assumes that S emissions reductions begin immediately but are achieved later, thereby increasing the total flux of S to the catchment within the 30 year timescale.

(v) Changes in the biogeochemical cycling of N are likely to influence the recovery and lead to lower ANC recovery than is predicted in this assessment.

At a wider European scale, MAGIC has been calibrated to key sites in the ICP-IM to assess the impact of a wide range of scenarios, including the Joint Optimisation, Reference and Maximum Feasible Reduction.

The model results showed that with the Maximum Feasible Reductions and the Joint Optimization scenario, the response variables (base saturation, pH, ANC) stabilize earlier and attain a higher level than with the Current Reduction Plans and the Reference scenarios. At the least acidified sites in Denmark and Finland the temporal response of the ecosystem to the Joint Optimization scenario is quite similar to that of the Reference scenario. At the UK, Norwegian and Swedish sites, the Joint Optimization scenario leads to an earlier and more pronounced improvement, compared with the Reference scenario.

The MAGIC results are consistent with two other dynamic acidification models; SAFE and SMART.

(iii) MAGIC model development

MAGIC is a lumped-parameter model of intermediate complexity, developed to predict the long-term effects of acidic deposition on surface water chemistry. The model simulates soil solution and surface water chemistry to predict average concentrations of the major ions. MAGIC calculates for each time step the concentrations of major ions under the assumption of simultaneous reactions involving sulphate adsorption, cation exchange, dissolution-precipitation-speciation of aluminium and dissolution-speciation of inorganic carbon. MAGIC accounts for the mass balance of major ions in the soil by book-keeping the fluxes from atmospheric inputs, chemical weathering, net uptake in biomass and loss to runoff.

At the heart of the MAGIC is the size of the pool of exchangeable base cations in the soil. As the fluxes to and from this pool change over time owing to changes in atmospheric deposition, the chemical equilibria between soil and soil solution shift to give changes in surface water chemistry. The degree and rate of change of surface water acidity thus depend both on flux factors and the inherent characteristics of the affected soils.

MAGIC has recently been extended to include functions for N retention and loss. The new version incorporates a soil C and N pool. The changes in size of the C pool are specified external to the model. Net plant uptake of N and loss to the atmosphere by denitrification are specified for each time step. At each time step leaching of N (N_{leach}) is the net result of N input in deposition (N_{dep}), net uptake by plants (N_{upt}), denitrification (N_{den}) and net immobilisation in the soil (N_{immob}).

$$N_{leach} = N_{dep} - N_{upt} - N_{den} - N_{immob}$$

If inputs in deposition are insufficient to satisfy N uptake and denitrification, the model assumes that the N required is taken from the soil N pool, thus increasing C/N ratio. This implies "mining" of the soil N pool to provide the N necessary to grow a forest, for example.

Net immobilisation of N in the soil is assumed governed by the C/N ratio of the soil organic matter pool following the general relationship derived from empirical data for coniferous forests in Europe. At high C/N immobilisation is 100% and at low C/N immobilisation is 0% of N is soil solution. These upper and lower limits are set as part of the model calibration. Ammonium (NH_4) and nitrate (NO_3) are treated separately. Nitrification rate is specified as the percentage of the soil NH_4 pool nitrified at each time step. Together these parameters allow calibration to the measured concentrations of NO_3 and NH_4 in runoff or leachate as well as to the C:N ratio in the soil for the reference year.

The major change in the new version of MAGIC is the addition of processes regulating nitrogen retention and release. Previous versions of MAGIC required that net catchment N retention be calibrated to match present day observed concentrations of NO_3 and NH_4 in surface water. This percentage net retention was then usually assumed to remain constant throughout the simulation period and so the model had no internal mechanism to simulate N saturation due to N deposition or changes in uptake by plants or soil. MERLIN, on the other hand, focuses entirely on N dynamics, and includes two plant compartments and two soil compartments with all the fluxes of N between the compartments either specified or modelled. MERLIN provides a more rigorous treatment of N cycling and nitrogen saturation, but requires a large amount of information on N and C pools and cycles in the ecosystem. Such information is generally lacking except for a few intensively studied research sites.

MAGIC now offers a compromise between the relatiely complex and data-intensive nitrogen model MERLIN and the simple empirical nitrogen functions in earlier versions of MAGIC. MAGIC does not replace MERLIN, however, because MERLIN can tackle the internal distribution of N within the ecosystem, and point to changes in plant C/N and mineralisation in response to changes in land-use, N deposition or climate. But MERLIN cannot be directly used to predict changes in acidification status of a site. The new approach in MAGIC appears to be satisfactory for simulation of response in N leaching following afforestation and N addition at Aber, and reduced N deposition and climate change at Risdalsheia and allows for associated changes in acid base chemistry to be modelled.

MAGIC is about as complex a process-oriented model for simulation of runoff chemistry as is practically feasible for the amount of data generally available from individual sites. Incorporation of additional parameters, processes and complexity would be at the expense of "transparency", and would require input data above and beyond that normally available on a regional scale. The model now offers a potential basis for regional scenario studies of changes in surface water chemistry under scenarios of combined changes of S and N deposition, land-use and climate.

4. Summary of achievements against objectives

Note that numbers relate directly to the objectives as specified in the contract.

Model development (1)

* The MAGIC model has been re-configured to incorporate catchment scale mass balance for N (see attachments 1 and 2).

* The new structure has been tested at ICP-IM sites (see attachment 3).

UK National Focal Centre for ICP-IM (2)

* IH staff have represented DETR at the annual ICP-IM Task Force Meetings in 1997 (Netherlands) and 1998 (Estonia).

Data collection at UK ICP-IM sites (3)

* Data collection has continued throughout the past two years at the two UK ICP-IM sites: Afon Hafren and Allt a Mharcaidh (see attachments 6 and 7).

* Links have been maintained with other UK organisations to provide a full suite of measurements to the ICP-IM.

Data summary and transmission (4)

* All data has been transferred annually to the ICP-IM data centre in Helsinki as part of our contribution to the annual report on ICP-IM (see attachments 6 and 7).

Trend analysis at UK ICP-IM sites(5)

* Data analysis has been undertaken each year to identify trends, particularly in deposition and runoff data (see attachment 6).

Co-ordination of dynamic modelling activities (6)

* IH has initiated and led a Dynamic Modelling sub-group of CLAG to co-ordinate the UK dynamic modelling effort (see attachment 4).

* IH initiated and took major part in a co-ordinated approach to a dynamic modelling assessment of deposition scenarios at ICP-IM sites across Europe as part of an EU-LIFE project (see attachments 3 and 4).

* Within the European context, IH staff participated in and presented key papers at EU workshops during 1996-1998 in the Netherlands, UK, Finland and Spain.

Scenario analysis (7)

* The MAGIC model has been used to assess the response of surface waters at UKAWMN sites to the Oslo Protocol and EU Acidification Strategy B1 scenarios (see attachments 4, 8 and 9).

* The MAGIC model has been used to assess the response of surface waters at European ICP-IM sites to a range of EU acidification strategy emission scenarios (see attachments 3, 5 and 10).

* The MAGIC model has been used to determine the likely response of surface waters to differences in timing of emission reductions at ICP-IM and UKAWMN sites (see attachments 3 and 8).

* The new version of MAGIC, incorporating N dynamics, has been used to explore coupled N and S emission reduction scenarios at ICP-IM sites (see attachment 3).

5. **<u>List of Attached Reports and Papers</u>** (Project Outputs)

1. JENKINS, A., FERRIER,R.C. and COSBY, B.J. 1997. A dynamic model for assessing the impact of coupled sulphur and nitrogen deposition scenarios on surface water acidification. *Journal of Hydrology*, 197, 111-127.

2. INTERNAL USER MANUAL (submitted by B.J.Cosby). 1998. Model of acidification of groundwater in catchments (MAGIC Version 7.00). Description of model structure and calibration procedures, including a new empirically-derived, process-based representation of nitrogen dynamics in catchments.

3. FORSIUS, M., GUARDANS, R., JENKINS, A., LUNDIN, L. and NIELSEN, E. (Eds). 1998. Integrated monitoring: environmental assessment through model and empirical analysis. Final results from the EU/Life-project 'Development of Assessment and Monitoring Techniques at Integrated Monitoring Sites in Europe'. Project LIFE95/FIN/A11/EPT/387. ISBN 952-11-0302-7, Helsinki.

4. JENKINS, A., RENSHAW, M., HELLIWELL, R., SEFTON, C.E.M., FERRIER, R.C. and SWINGEWOOD, P. 1997. Modelling surface water acidification in the UK: Application of the MAGIC model to the Acid Waters Monitoring Network. *IH Report 131*. Institute of Hydrology, Wallingford.

5. FORSIUS, M., ALVETEG, M., BAK, J., GUARDANS, R., HOLMBERG, M., JENKINS, A., JOHANSSON, M., KLEEMOLA, S., RANKINEN, K., RENSHAW, M., SVERDRUP, H. and SYRI, S. 1997. Assessment of the Effects of the EU Acidification Strategy: Dynamic Modelling on Integrated Monitoring Sites. First results. ISBN 952-11-0979-3, Helsinki.

6. KLEEMOLA, S. and FORSIUS, M. (Eds). 1997. 6th Annual Report 1997. UN ECE Convention on Long-Range Transboundary Air Pollution. International Co-operative Programme on Integrated Monitoring of Air Pollution Effects on Ecosystems. ISBN 952-11-0587-9, Helsinki.

7. KLEEMOLA, S. and FORSIUS, M. (Eds). 1998. 7th Annual Report 1998. UN ECE Convention on Long-Range Transboundary Air Pollution. International Co-operative Programme on Integrated Monitoring of Air Pollution Effects on Ecosystems. ISBN 952-11-0301-9, Helsinki.

8. JENKINS, A. and RENSHAW, M. 1997. An Assessment of the EU Acidification Strategy B1 Scenario and the Timing of Emission Reductions using the MAGIC Model at UKAWMN Sites. A report to DETR under contract No. EPG 1/3/84. Institute of Hydrology, Wallingford.

9. JENKINS, A., HELLIWELL, R.C., SWINGEWOOD, P.J., SEFTON, C.E.M., RENSHAW, M. and FERRIER, R.C. 1998. Will reduced sulphur emissions under the Second Sulphur Protocol lead to recovery of acid sensitive sites in UK? *Environmental Pollution*, **99**, 309-318.

10. FORSIUS, M., ALVETEG, M., JENKINS, A., JOHANSSON, M., KLEEMOLA, S., LUKEWILLE, A., POSCH, M., SVERDRUP, H. and WALSE, C. 1998. MAGIC, SAFE and SMART Model Applications at Integrated Monitoring Sites: Effects of Emission Reduction Scenarios. *Water, Air and Soil Pollution*, **105**, 21-30.

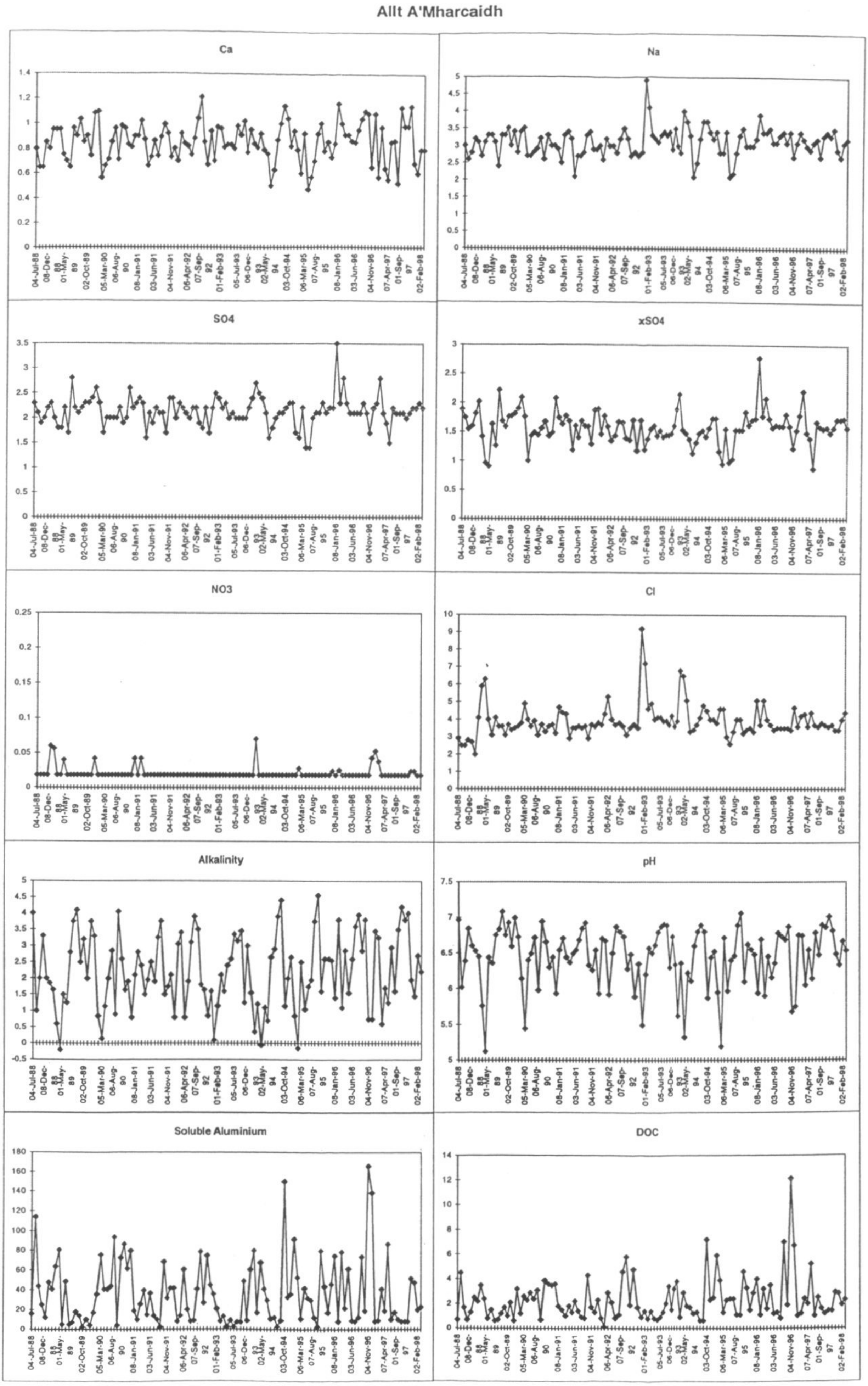

Figure 1 Stream chemistry for the Allt a'Mharcaidh. Units are μeq/l except for pH and Al (μg/l)

Afon Hafren

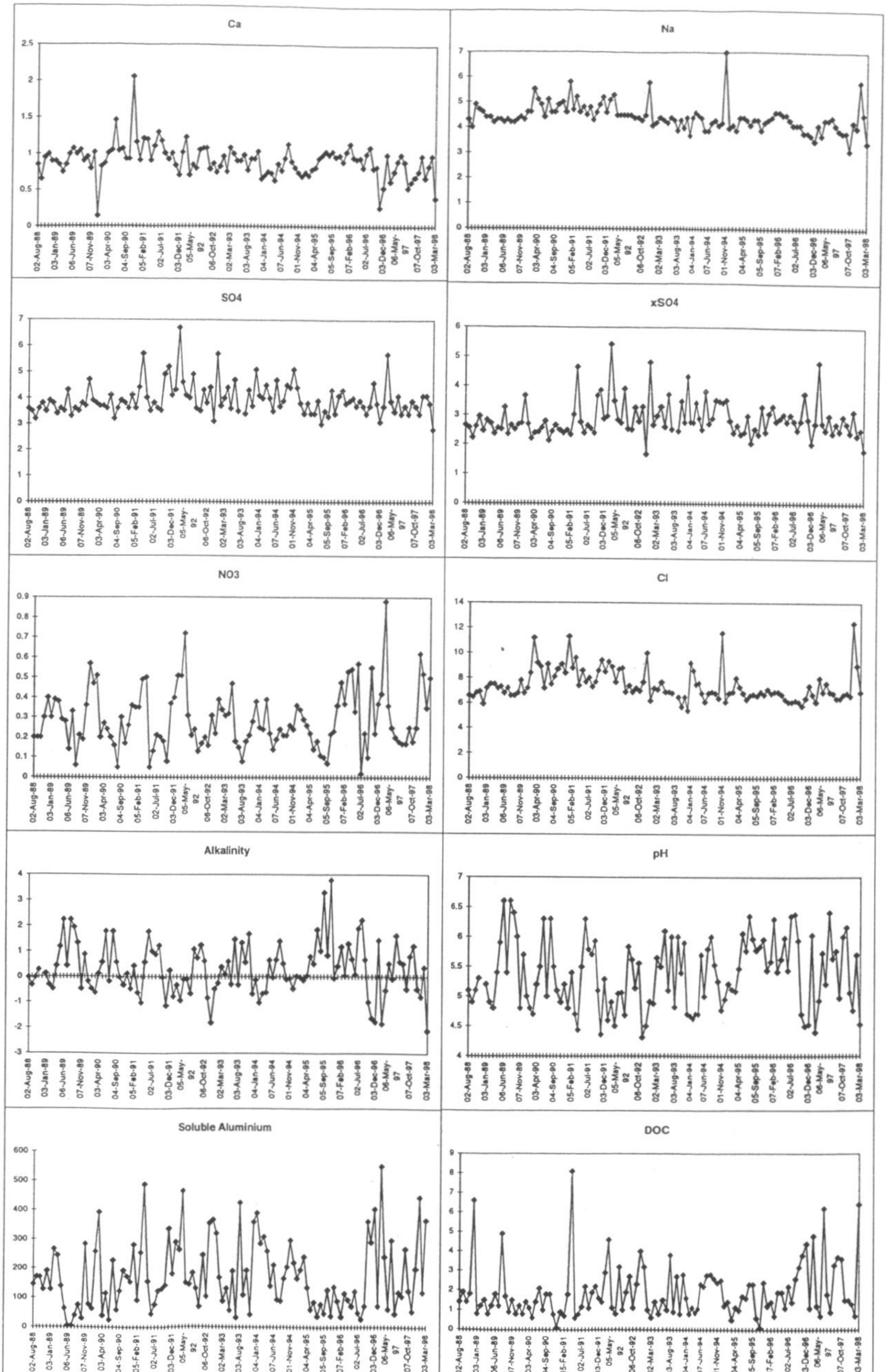

Figure 2 Stream chemistry for the Allt a'Mharcaidh. Units are µeq/l except for pH and Al (µg/l)