

Predicting regional recovery from acidification; the MAGIC model applied to Scotland, England and Wales

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Abstract

A dynamic, process-based model of surface water acidification, MAGIC, has been applied to over a thousand sites across the UK. The model is calibrated to surface water samples collected during a survey for the Critical Loads programme, and utilises the best available and consistent estimates of soil physical and chemical properties, rainfall and runoff volumes, and deposition chemistry. A total of 698 sites were calibrated successfully. At these sites, surface water chemistry was reconstructed from 1850 to the present day, and forecast to 2050 based on future decreases in sulphur (S) deposition in response to the Second S Protocol.

Model outputs capture distinct regional patterns of acidification and recovery. The most acidic present-day conditions are found in acid-sensitive regions of Northern England (the Pennines, Lake District and North York Moors). Although a significant proportion of sites in these areas failed to calibrate, those that did are predicted to have experienced severe historic decreases in acid neutralising capacity (ANC) in response to high levels of acidic deposition. The model also indicates significant acidification in the moderate deposition areas of Wales and Galloway, whereas in the low deposition region of northern Scotland, acidification has been minor even in areas of acid-sensitive geology. ANC is forecast to recover at virtually all sites, with the greatest recovery predicted for areas currently subject to high deposition. The model indicates that the Second S Protocol, however, will not be sufficient to produce full recovery, with average ANC increases to 2050 counteracting just 27% of the simulated decline from 1850 to present day. Acidic conditions (ANC < 0) are predicted to persist until 2050 at a significant number of sites in Northern England, Wales and Galloway.

Introduction

Dynamic hydrochemical models, such as MAGIC (Model of Acidification of Groundwater in Catchments) (Cosby *et al.*, 1985) perform a central role in the determination and assessment of policy aimed at regulating emissions of acidifying pollutants to the atmosphere. They provide the only opportunity to determine the level of emission reduction required to achieve a given surface water chemistry target (for example, acid neutralising capacity (ANC) > 0 $\mu\text{eq l}^{-1}$) within a given time period. They also quantify the potential time-lag between emission reduction and chemical recovery and assess the degree of recovery (or, conversely, the damage) to be expected in the future if an emission reduction target (such as a critical load) is, or is not, achieved.

The first step in using dynamic models in this process is the rigorous application to individual sites (or catchments) for which detailed soil and water chemistry, land use and physical data exist. In the UK, the sites which comprise the Acid Waters Monitoring Network (UKAWMN) have formed the basis of a detailed model-

ling study using the MAGIC model (Jenkins *et al.*, 1997). The calibrated model for each of the 21 sites was used to assess future surface water acidity status under agreed atmospheric emission reduction scenarios relating to established UNECE agreements (the Second Sulphur Protocol). This analysis used high frequency and high quality data from the sites to calibrate the model and so provided a rigorous model application. On the other hand, the relatively small number of UKAWMN sites does not fully represent acid-sensitive regions of the UK (Patrick *et al.*, 1996). Therefore, the next phase of modelling assessment is to extrapolate model applications to larger spatial scales, in this case, to the whole of Scotland, England and Wales.

Model applications at these large spatial scales are usually data limited; that is, they can only be applied if data at the relevant spatial scale are available or can be derived, assumed or extrapolated. Furthermore, the model calibration relies upon mean water chemistry calibration targets and, at a large spatial scale, water samples are rarely taken more than once. Consequently, the model calibration is

critically dependent on the degree to which the single water sample represents the mean annual water chemistry.

Two general techniques can be utilised to achieve a regional model application: (i) the construction of statistical representations of the characteristics of a region and the employment of some statistical sampling methodology, such as Monte-Carlo analysis, and (ii) a site-specific model calibration to a great number of sites within a region using best available data for each site. The Monte-Carlo procedure does not calibrate individual models to water and soil data for each site, but attempts merely to reproduce the frequency distributions of water and soil chemistry characteristics across the whole region. In this respect, the calibrated model cannot be used to predict the future behaviour of a specific individual lake or stream, but provides information on the percentage of surface waters that are likely to recover within the region as a whole. The critical assumption now becomes that the characteristics of the surface waters sampled represent the actual characteristics of the regional population. This technique has been employed successfully in an applications of MAGIC to Wales (Sefton and Jenkins, 1997) and to southern Norway (Cosby and Wright, 1998).

This paper uses the site-specific methodology, whereby not only are the sites sampled assumed to represent the regional water chemistry, but the available water chemistry is assumed to represent the mean at each site, and further assumptions are made related to extrapolation of soil pit data across whole catchments. This model application to 1027 sites in Scotland, England and Wales is based primarily on the surface water chemistry database collected as part of the UK Critical Loads Research Programme (Battarbee, 1995), and draws best available information from a range of existing environmental databases. The resulting model is used in conjunction with a distributed emission and deposition model to predict the impact of the Second Sulphur Protocol across the UK.

Model calibration

The basis of the site-specific methodology is that each calibration throughout the region conforms to a standard methodology and utilises consistent data. In many respects, the consistency of the data is the biggest issue since the resolution of available spatial data tends to decrease with increasing spatial scale. Consequently, many of the data sets available at a UK scale need to be disaggregated or transformed to provide the necessary data for model calibration.

DATA REQUIREMENTS

The site-based application of MAGIC requires data for each site on a range of physical and chemical properties. Site specific data input to the model include annual rainfall and runoff volumes, deposition chemistry and soil

depth, bulk density, porosity and cation exchange capacity (CEC). The model is calibrated to eight measured 'target variables'; surface water concentrations of the base cations calcium (Ca), magnesium (Mg), sodium (Na) and potassium (K), and soil exchangeable fractions of the same ions.

DATA SOURCES

Surface water chemistry

At the outset of the Surface Water Critical Loads programme, a single surface water sample was collected from within each of 1573 10-km grid squares across the UK (Kreiser *et al.*, 1995). The sample points were selected to represent the most acid-sensitive water body within each 10-km square based on altitude and geology. Since only a single sample was taken from each site, standing waters (lakes or reservoirs) were chosen rather than running waters. Where no standing waters were present within the square, a headwater stream was used. All chemical analyses were undertaken at a single laboratory, and were subject to rigorous quality assurance and control procedures.

Soils data

Soil depth, porosity, bulk density, CEC and exchangeable base cation fractions were estimated from mean data for individual soil series at a national scale. For each catchment, the proportions of total area occupied by different soil series were determined, and used to calculate spatially weighted mean values for each soil variable. In Scotland, soil data were supplied and processed by the Macaulay Land Use Research Institute. For English and Welsh sites, data were supplied by the Soil Survey and Land Resource Centre, and processed at University College London. Further details of the methods used to estimate soil properties, and their influence on the MAGIC application to the Critical Loads sites in Scotland, are provided by Helliwell *et al.* (1998).

Deposition chemistry

Wet deposition of major ions is monitored on a weekly basis at 32 sites across the UK as part of the Acid Deposition Monitoring Network (Devenish, 1986). AEA Technology's National Environmental Technology Centre (NETCEN) administers the network and produces national estimates of wet deposition at a 20-km resolution. For the current study, mean values were taken for 1989–1992, the period during which the Critical Loads Survey was carried out. The NETCEN data do not incorporate dry deposition inputs, or the possible effects of orographic enhancement such as seeder-feeder mechanisms (Fowler *et al.*, 1988). In order to generate realistic deposition inputs for the model, these factors need to be estimated. Although a model has been developed to reproduce seeder-feeder effects for the NETCEN data (Dore *et al.*, 1992), the resulting wet deposition fluxes were not found

to relate well to calculated output fluxes of conservative (Cl) and pseudo-conservative (SO₄) ions at the study sites. In a number of high-elevation areas, notably north-central Scotland, enhanced wet-deposition input fluxes greatly exceeded observed stream output fluxes.

Since it is essential for MAGIC that conservative ions are simulated accurately, deposition was estimated using a method previously employed in the application of MAGIC to sites in the UKAWMN (Jenkins *et al.*, 1997). This uses NETCEN estimates of wet deposition to calculate input fluxes of Cl and SO₄. In most instances, this produced an excess of outputs over inputs, which is attributable to unmeasured dry deposition and underestimated wet deposition. In order to balance inputs, Cl was added to the NETCEN deposition value in the form of neutral sea salt, with base cations and sulphate added in amounts proportional to ratios in seawater (0.86 for Na, 0.019 for K, 0.21 for Mg, 0.04 for Ca and 0.104 for SO₄). Additional SO₄ was then added, if required, to match the observed stream output flux, on the basis that S adsorption is currently minimal. This is assumed to represent a combination of dry deposited SO₂ and SO₄ aerosols. Inputs of nitrate (NO₃) and ammonium (NH₄) were not changed from wet deposition values, and are thus likely to be underestimated. However, given the highly simplified treatment of nitrogen dynamics by MAGIC, this is unlikely to affect significantly model outputs.

Rainfall and runoff volumes

Rainfall and runoff were obtained from an Institute of Hydrology dataset, in which monthly rainfall values at a 1-km resolution are derived by interpolation of data from Meteorological Office rain gauges. Mean annual rainfall values were aggregated to the required 10-km resolution. Annual runoff values were derived from 1-km annual rainfall using interpolated estimates of evapotranspiration, and also aggregated to a 10-km resolution.

IDENTIFICATION OF SUITABLE SITES

Of the 1573 sites originally sampled, 236 could not be used for modelling due to a lack of input data. (This includes all of Northern Ireland, for which soils data were not available). Cl and SO₄ fluxes for the remaining 1337 sites were then checked for potential internal sources of these 'conservative' ions. A threshold was defined whereby, if the amount of Cl or SO₄ added exceeded 80% of the total input, this was considered indicative of an internal source. This led to the exclusion of a further 350 sites, predominantly in lowland areas such as the Midlands and East Anglia (Fig. 1). It seems probable that, in these regions, agricultural or other local anthropogenic sources may be significant, or alternatively that Cl or SO₄ may be released through weathering or contact with saline geologic (connate) water during deep groundwater circulation. In either case, these catchments would not be suitable for MAGIC application.

Despite using unenhanced deposition data, at a number of sites, primarily in north-central Scotland, estimated Cl and/or SO₄ inputs still exceeded outputs (Fig. 1). Given what appears to be strong regional consistency, this is unlikely to reflect problems with surface water sampling, and may therefore imply an overestimation of the wet deposition fluxes. To balance inputs and outputs at these sites, sea salts and SO₄ were removed from deposition in a procedure equivalent to the addition described above. These sites were retained in the analysis, leaving a total of 1027 sites in the final regional calibration.

Calibration procedure

Calibration of MAGIC was undertaken in two stages. Firstly, observed surface water NO₃ and NH₄ concentrations were matched to deposition inputs using a simple first-order uptake function. Secondly, an iterative procedure was used to fit long-term model simulations to present day measurements of the target soil and water variables. Simulations were run from 1852 to 1992 using a historical deposition sequence generated by scaling currently-observed deposition to a reconstruction of UK S and N emissions (Warren Spring Laboratory, 1983, 1987).

Because many of the input variables in the calibration are uncertain, a 'fuzzy' optimisation method was employed. Multiple calibrations were undertaken for each site, and in each case the measured ('fixed') input parameters were randomly perturbed within estimated uncertainty bands. Unmeasured parameters (base cation weathering rates and soil base cation selectivity coefficients) were considered 'adjustable', and optimised within the calibration. Uncertainty bands for surface water target variables were estimated as whichever was the greater of 5 eq/l or 10%. For soil base cation exchange fractions, expressed as a percentage, a fixed uncertainty band of 0.5% was used below an exchange fraction of 5%. Above this value, a variable uncertainty band (10% of the exchange fraction value) was used. Any simulation able to reproduce values of all eight target variables within these uncertainty bands was considered acceptable, and average values of optimised parameters from these successful calibrations were used to perform forecasts. Further details of the MAGIC calibration procedure are provided by Cosby *et al.* (1985) and Jenkins *et al.* (1997).

Results of calibrations

Initially, 661 out of the 1027 suitable sites were successfully calibrated; they provided a reasonable coverage of acid-sensitive areas of the UK (Fig. 2). Simulated present-day surface water ANC for all successfully calibrated sites is in good agreement with observed values (Fig. 3). However, in some areas, a significant number of sites could not be calibrated to match observed data, for which two major causes have been identified.

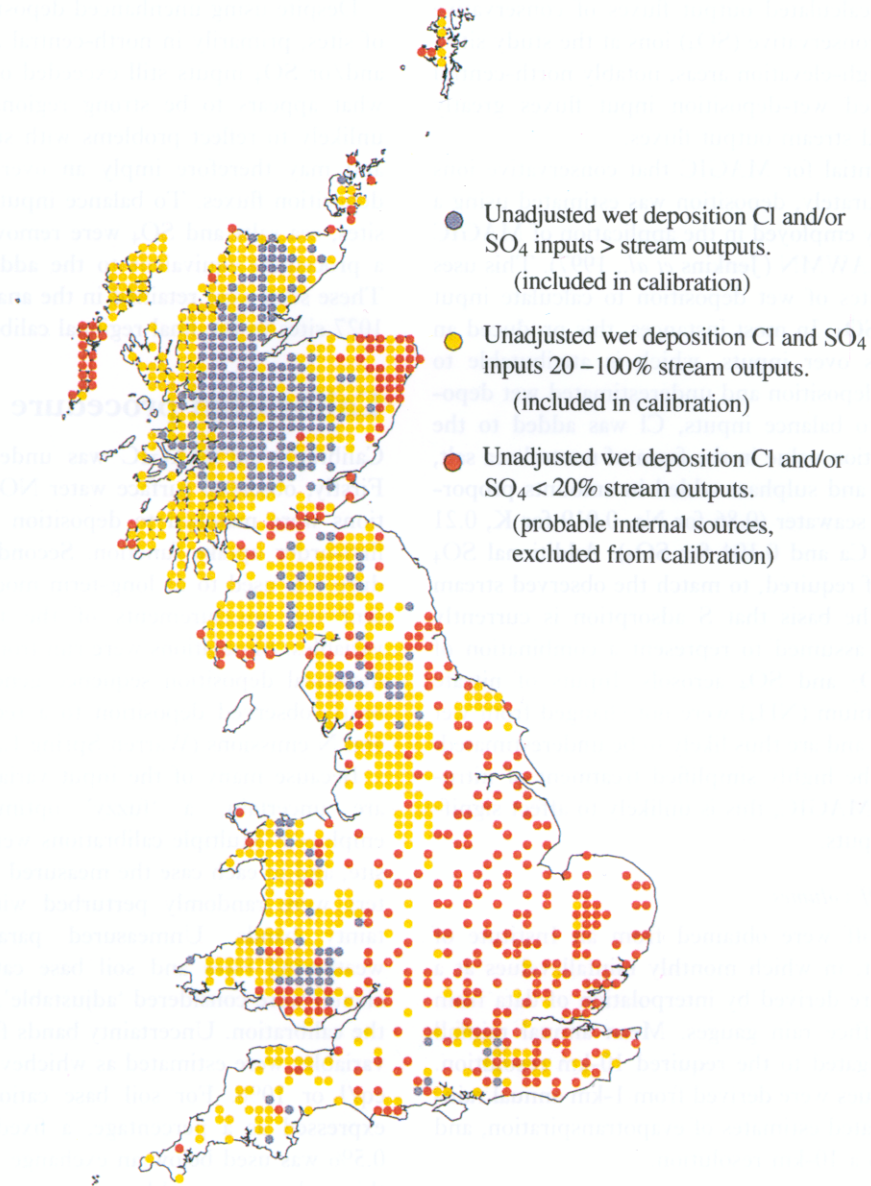


Fig. 1. Acceptability of Cl and SO₄ balances.

One region where a large number of sites failed to calibrate was north-west Scotland, particularly close to the coast. Examination of these sites indicates that, in virtually every case, the reason for failure was a high simulated value for surface water Mg relative to that observed. This could be linked to a probable 'seasalt' event in the period preceding May 1990 when most samples in the area were collected; this was identifiable in significantly above-average Cl concentrations for this period at the two UKAWMN sites in the region, Loch Coire nan Arr and Allt na Coire nan Con (Patrick *et al.*, 1995). Seasalt events, in which large quantities of marine ions are deposited on the catchment, can generate high concentrations of Cl in runoff, whilst the marine cations Na and Mg temporarily

displace H ions from soil-exchange sites (Skartveit, 1981; Langan, 1989). This effect has significant consequences for model calibration, since the single sample is assumed to represent the annual mean concentration. Due to the method used to estimate deposition, the elevated surface water Cl concentration leads to overestimation of both annual Cl inputs, and annual inputs of other marine ions. In the case of the marine cations, particularly Mg in this region, temporary soil retention means that this enhanced input is not reflected in the surface water sample, and the model cannot be calibrated. Fig. 4 illustrates this problem further; there is a clear relationship between non-marine Mg concentration (the surface water Mg concentration after the marine component, calculated from the seawater

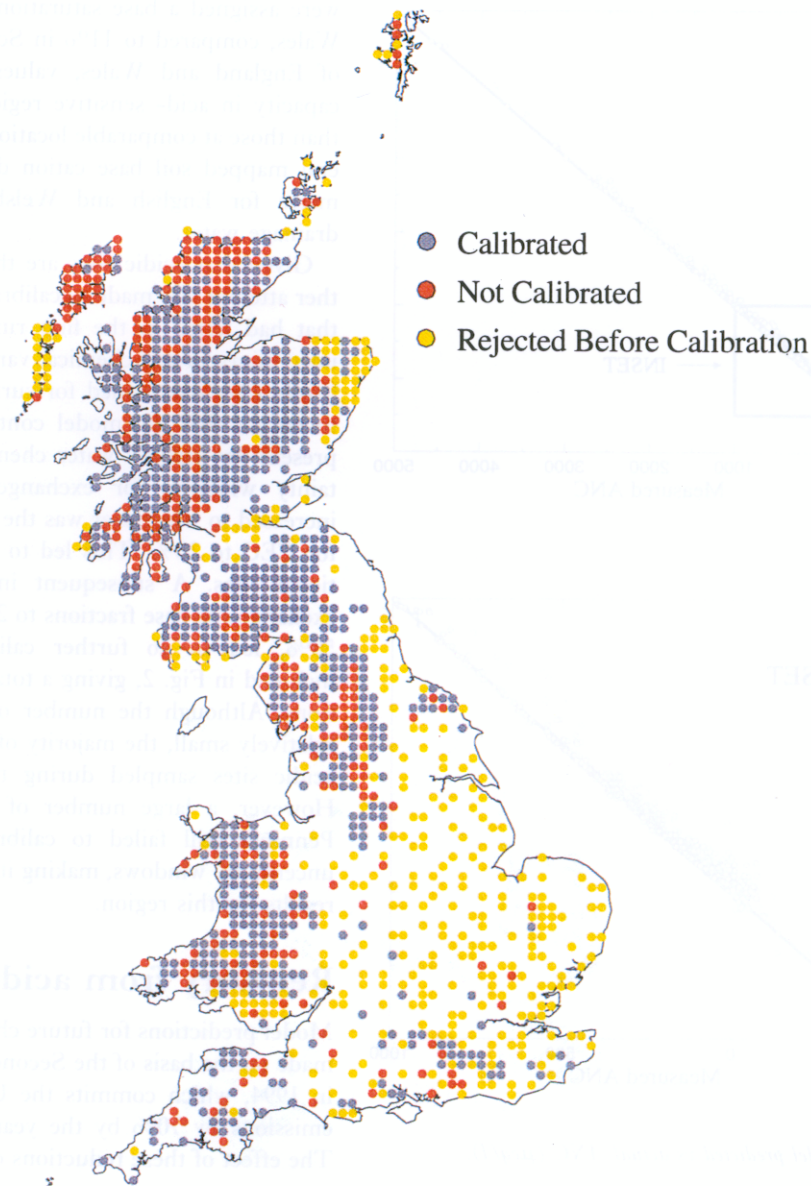


Fig. 2. Sites successfully calibrated by MAGIC.

ratio of Mg to Cl, has been removed) and success or failure of calibration (Fig. 4). A negative non-marine Mg implies that the cation is being retained within the soil, a temporary phenomenon which is not characteristic over the longer timescale on which MAGIC operates.

A second, less extensive area where a large number of sites failed to calibrate was the Lake District region of northwest England. Here the problem appeared similar, although in this case it was commonly Na that was over-predicted in the calibration rather than Mg. Again, this is thought to represent the aftermath of a sea-salt event. Most samples in this region were collected in May 1991, and around this time Cl concentrations at Burnmoor Tarn and Scoat Tarn, the two Lake District UKAWMN sites,

were among the highest recorded over 9 years of sampling.

Finally, a significant number of sites failed to calibrate in the Pennine region (central northern England). Examination of model outputs indicated a quite different problem to that encountered in the regions described above, with MAGIC unable to replicate high observed values for soil exchangeable cations. Almost all of these sites have highly acidic surface waters, and similar problems could also be identified at other low-ANC sites failing to calibrate in England and Wales. Comparison between soils data for England and Wales and for Scotland suggested substantial differences in the compositions assigned to different soil types. For example, blanket peats, which dominate many acid-sensitive catchments in the Pennines,

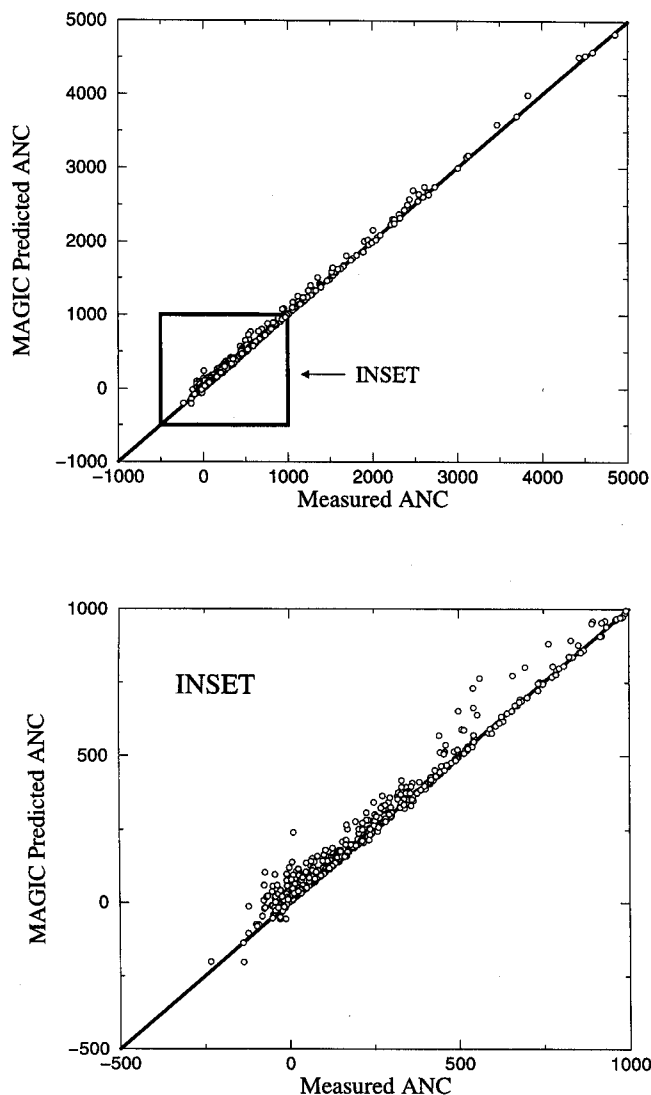


Fig. 3. Model predicted vs actual ANC ($\mu\text{eq/l}$).

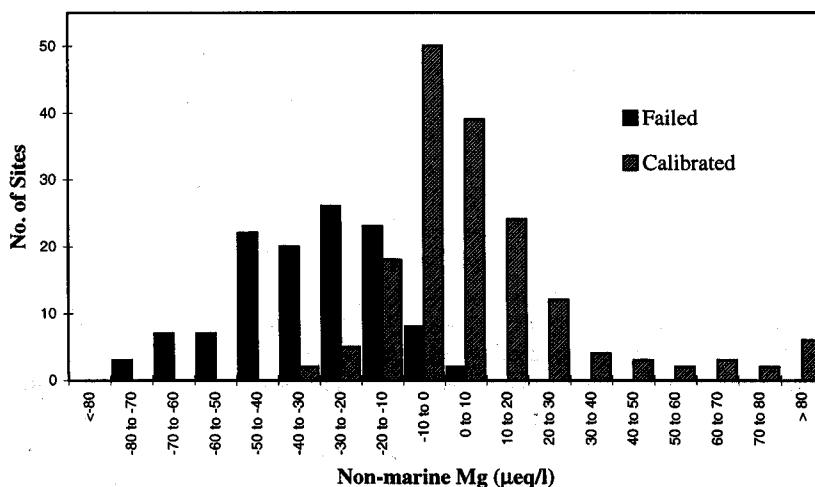
were assigned a base saturation of 23% for England and Wales, compared to 11% in Scotland. Throughout much of England and Wales, values of soil cation exchange capacity in acid-sensitive regions were markedly higher than those at comparable locations in Scotland, and in general mapped soil base cation data may provide overestimates for English and Welsh catchments with acidic drainage water.

Given that acidic sites are the focus of concern, a further attempt was made to calibrate English and Welsh sites that had failed in the first run, by allowing for greater uncertainty in soil chemical variables. Narrow uncertainty bands were maintained for surface water target variables, to ensure that the model continued to generate realistic present-day surface water chemistry. Initially, the uncertainty windows for exchangeable base fractions were increased to whichever was the greater of 1.0 or 20%, and for CEC to 20%. This led to the calibration of 11 additional sites. A subsequent increase in uncertainty for exchangeable base fractions to 2.0 or 50%, and for CEC to 50%, led to 26 further calibrations. These sites are included in Fig. 2, giving a total of 698 successful calibrations. Although the number of additional calibrations is relatively small, the majority of these are among the more acidic sites sampled during the Critical Loads survey. However, a large number of highly acidic sites in the Pennines still failed to calibrate despite increased soil uncertainty windows, making it difficult to interpret model results for this region.

Recovery from acidification

Model predictions for future changes at calibrated sites are made on the basis of the Second Sulphur Protocol, ratified in 1994, which commits the UK to reducing national S emissions by 70% by the year 2005, and 80% by 2010. The effect of these reductions on deposition has been sim-

Fig. 4. Relationship between site calibration and non-marine Mg concentration, NW Scotland.



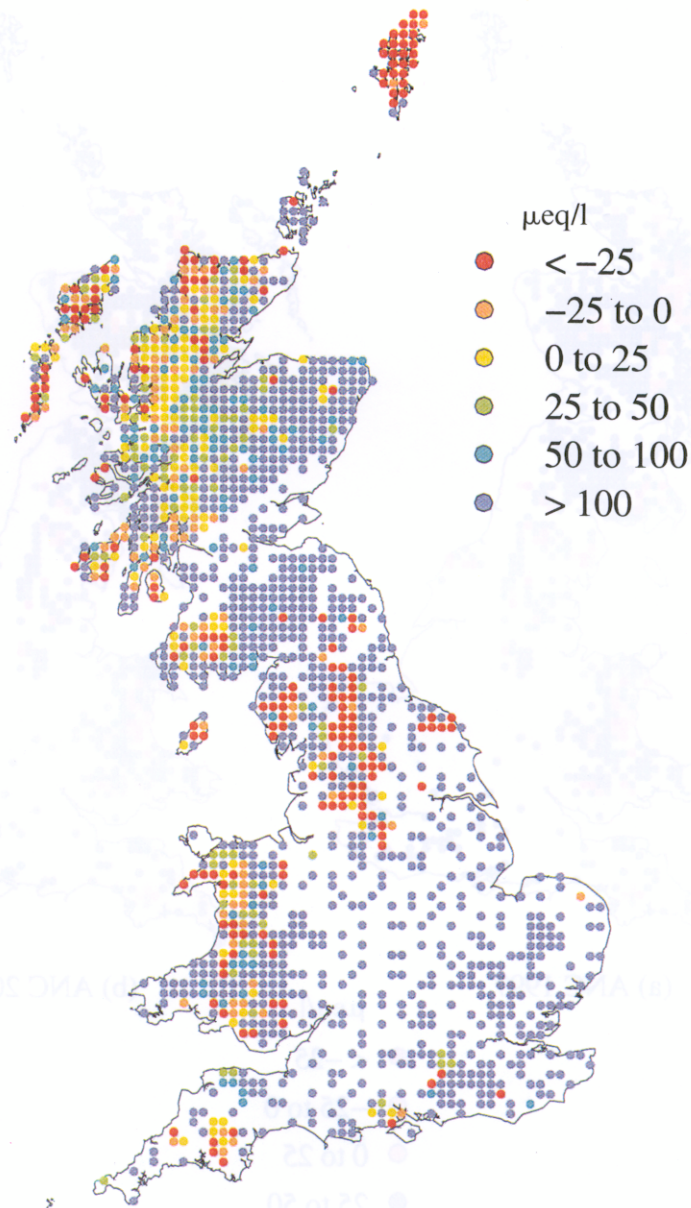


Fig. 5. Measured ANC, Critical Loads sites.

ulated by the Hull Acid Rain Model (HARM) at a 20-km resolution across the UK (Metcalf *et al.*, 1989; Metcalfe and Whyatt, 1995). Predicted future deposition as a percentage of present-day deposition was determined for each calibrated site, and used to simulate changes in surface water chemistry to the year 2050.

The measured surface water ANC at all Scotland, England and Wales Critical Loads sites show clear spatial patterns (Fig. 5). The most intensive clustering of low-ANC sites is in northern England—the Pennines, central Lake District and North York Moors—where sensitive geologies exist in close proximity to pollution sources. Significant numbers of low-ANC surface waters also occur in the moderate deposition areas of North Wales, Galloway

(SW Scotland) and Dartmoor (SW England), and also in Scottish coastal areas. The Scottish coastal sites were sampled following a sea-salt episode, however, and the low ANCs measured may not represent longer-term annual means.

The number of calibrated (Figs. 6 and 7) sites is considerably less than the total sampled (Fig. 5). Coverage for mainland Scotland remains good, as does that for Wales, but relatively few of the acidic sites in England, particularly in sensitive northern areas, were successfully calibrated. The extent to which conclusions can be drawn regarding future changes in these areas is thus limited.

For northern Scotland, present-day modelled ANC (Fig. 6a) appears to differ significantly from measured

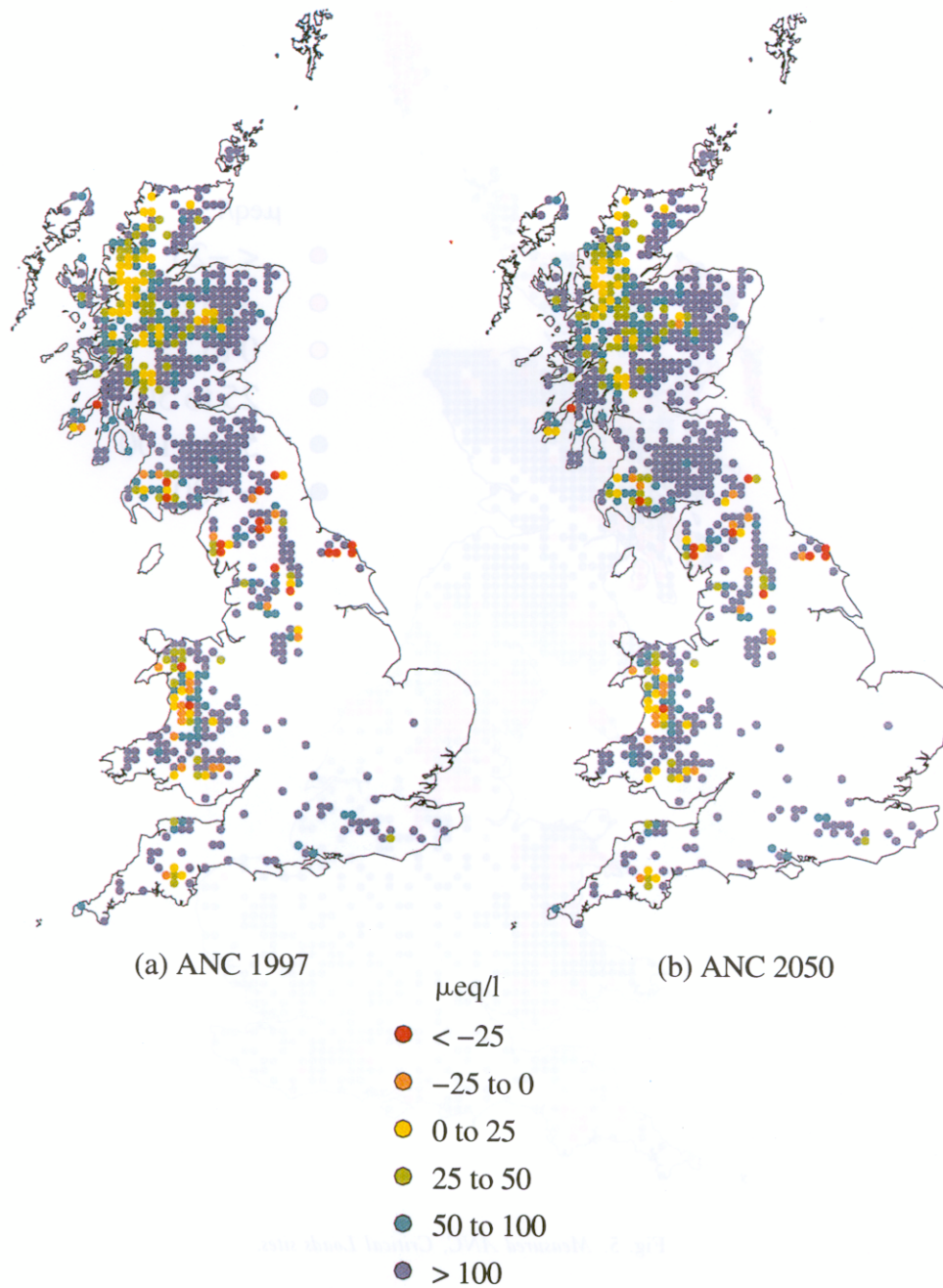


Fig. 6. *MAGIC* modelled ANC, 1997 and 2050 (Second Sulphur Protocol).

values (Fig. 5). This results from the removal of sites affected by sea-salt acidification, and consequently the reduced dataset in Fig. 6a may actually provide a more realistic indication of acid status in the region than the full dataset (Fig. 5). The sites retained in the model show a clear spatial gradient in acidity, with ANC lowest in high-rainfall, high-elevation western catchments and highest in the dryer, lower elevation areas further east. For virtually all surface waters in this region, however, results suggest that mean ANC levels remain above zero, consistent with

low historic levels of acid deposition. This is also evident in the small modelled historic ANC decreases (Fig. 7a and Table 1). Given that very little acidification has occurred in the past, future recovery is likely to be negligible (Figs. 6b and 7b, Table 1).

Southern Scotland shows a different pattern, with greater historic acidification (Fig. 7a), and a cluster of sites with low or negative modelled present day ANC in the Galloway region. These sites are predicted to show very little recovery in response to projected future emission

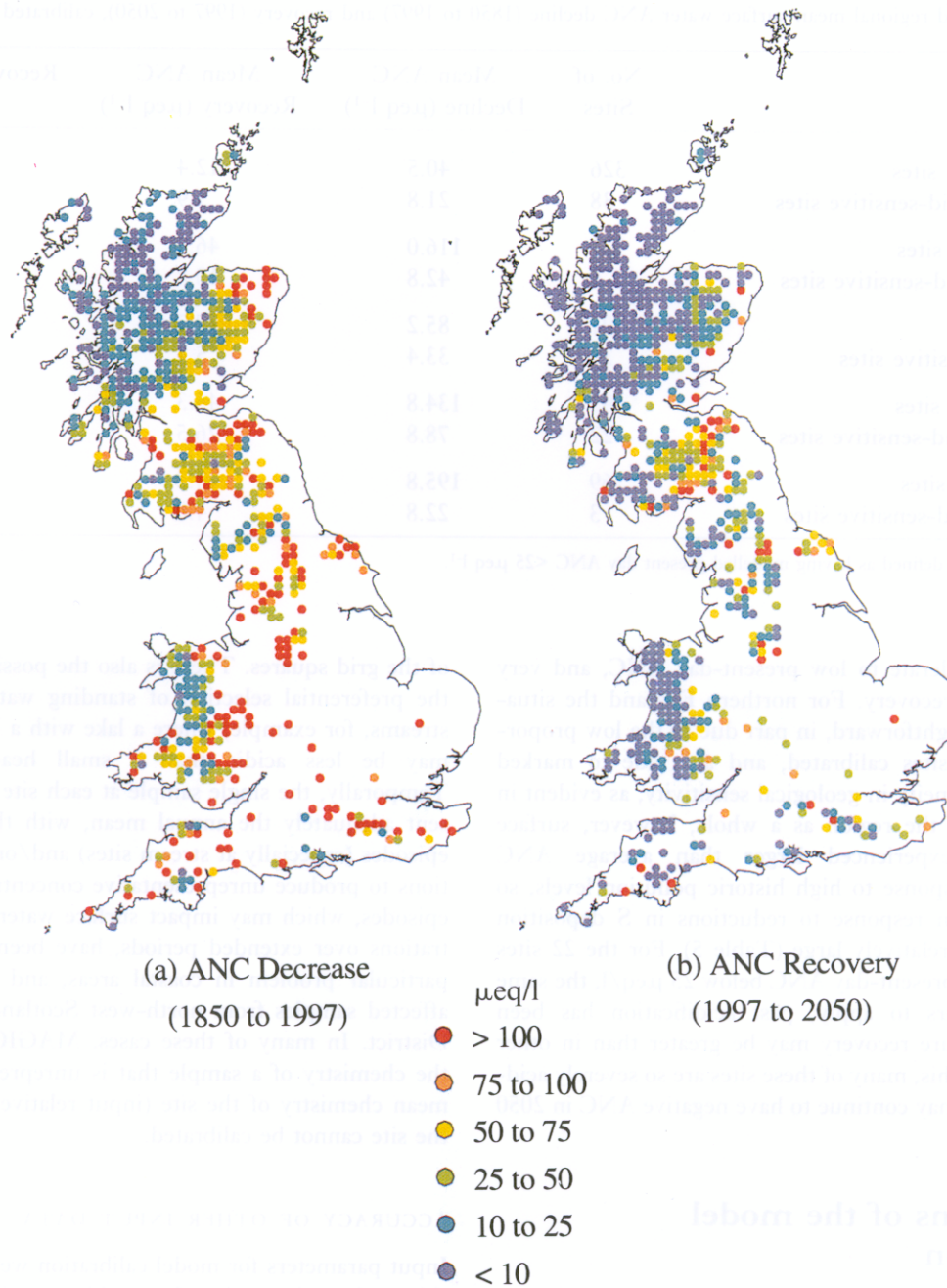


Fig. 7. Modelled decline and recovery in ANC.

reductions, with ANC at three sites remaining negative in 2050. Sites on less sensitive geology further east, although they have experienced large ANC decreases since 1850, have not become acidic.

In Wales, the spatial pattern of modelled present day ANC (Fig. 6a) agrees closely with observations (Fig. 5), with the majority of acidic sites in the mountains of north Wales. As in Galloway, Welsh surface waters have experienced a moderate degree of historic acidification, but future recovery at many sites, especially those which are

currently most acidic, is predicted to be minimal (Fig. 7, Table 1). Similar results and spatial patterns have been obtained for Wales by Collins and Jenkins (1998), in an application of MAGIC to 102 streams monitored during 1995 for the Welsh Acid Waters Survey.

It is less easy to interpret results for England due to the relatively poor success rate of calibrations. In southern England, the only extensive acid-sensitive area is Dartmoor, where the five calibrated sites suggest a situation similar to that in Wales; moderate historic acidification is

Table 1. Modelled regional mean surface water ANC decline (1850 to 1997) and recovery (1997 to 2050), calibrated sites.

Region	No. of Sites	Mean ANC Decline ($\mu\text{eq l}^{-1}$)	Mean ANC Recovery ($\mu\text{eq l}^{-1}$)	Recovery/Decline
N. Scotland, all sites	326	40.5	12.4	28.5%
N. Scotland, acid-sensitive sites	38	21.8	5.9	27.1%
S. Scotland, all sites	137	116.0	46.5	35.9%
S. Scotland, acid-sensitive sites	6	42.8	10.8	28.5%
Wales, all sites	101	85.2	17.7	24.0%
Wales, acid-sensitive sites	20	33.4	5.4	17.7%
N. England, all sites	95	134.8	45.3	27.7%
N. England, acid-sensitive sites	22	78.8	26.5	29.6%
S. England, all sites	69	195.8	44.2	18.6%
S. England, acid-sensitive sites	3	22.8	4.0	15.9%

Acid-sensitive sites defined as having modelled present day ANC $<25 \mu\text{eq l}^{-1}$.

coupled to moderate to low present-day ANC, and very limited future recovery. For northern England the situation is less straightforward, in part due to the low proportion of acidic sites calibrated, and also due to marked spatial heterogeneity in geological sensitivity, as evident in Fig. 5. Taking the region as a whole, however, surface waters have experienced larger than average ANC decreases in response to high historic pollution levels, so that recovery in response to reductions in S deposition should also be relatively large (Table 5). For the 22 sites with modelled present-day ANC below $25 \mu\text{eq/l}$, the same situation appears to apply; past acidification has been severe, but future recovery may be greater than in other areas. Despite this, many of these sites are so severely acidified that they may continue to have negative ANC in 2050 (Fig. 6b).

Limitations of the model application

Although model outputs indicate regionally consistent trends, these outputs are subject to a number of uncertainties. These can be divided into three main categories.

REPRESENTATIVENESS OF SURFACE WATER SAMPLES

There are issues of concern regarding both the spatial and temporal representativeness of the surface water chemistry samples. Spatial issues relate to the sampling strategy of the Critical Loads Survey. The intention of the survey was to sample the most acid-sensitive water body within each 10-km square, but a validation study by Curtis *et al.* (1995) indicated that the procedure may have failed to select a water body in the most sensitive critical load class in 1/3

of the grid squares. There is also the possibility of bias in the preferential selection of standing waters rather than streams, for example, where a lake with a large catchment may be less acidic than a small headwater stream. Temporally, the single sample at each site may not represent adequately the annual mean, with the potential for episodes (especially at stream sites) and/or seasonal variations to produce unrepresentative concentrations. Sea-salt episodes, which may impact surface water solute concentrations over extended periods, have been identified as a particular problem in coastal areas, and appear to have affected samples from north-west Scotland and the Lake District. In many of these cases, MAGIC cannot match the chemistry of a sample that is unrepresentative of the mean chemistry of the site (input relative to output) and the site cannot be calibrated.

ACCURACY OF OTHER INPUT DATA

Input parameters for model calibration were estimated for this study and are, therefore, subject to significant uncertainties. MAGIC was unable to replicate high base cation exchange fractions at many of the more acidic sites. By employing a single 'averaged' composition for each soil type across a wide area, the spatial weighing method for estimating soil composition may fail adequately to reflect local variations in base status. Differing sources of soils data for Scotland and England and Wales may also have introduced a degree of regional bias. The issues relating to the estimation of soil characteristics for MAGIC are discussed in greater detail by Helliwell *et al.* (1998).

Among the other input data, errors in the estimation of rainfall to runoff ratios are probably relatively minor in terms of their impact on calibrations. Errors in the estimation of deposition, however, may be significant.

Deposition is interpolated at a 10-km resolution from a limited number of wet deposition gauges, without taking account of orographic enhancement or dry deposition. Although a mass balance method has been used in an attempt to incorporate these factors, this approach remains an approximation, and is highly dependent on the representativeness of single surface water samples used to determine outputs.

PROCESSES NOT ACCOUNTED FOR WITHIN THE MODEL

In the model application described here, several catchment-related factors were ignored. Chief among these was the impact of land use, including the influence of forestry, agriculture and other local anthropogenic contaminant sources. MAGIC can incorporate the impact of forestry, but data requirements in terms of forest area and planting history are high, and proved difficult to quantify for the large number of sites considered in this regional application. Collins *et al.* (1998) have modelled the impact of forestry at 57 sites in the Welsh Acid Waters Survey, and results indicate that this significantly reduces, or in some cases negates, any future recovery. It is, therefore, likely that, at forested Critical Loads sites, recovery will be less than that predicted in the present study. MAGIC is less well suited to lowland agricultural catchments, and consequently these sites were largely excluded from analysis on the basis of apparent internal sources of Cl or SO₄. Again, it would be difficult to quantify agricultural factors without major additional data collection.

Finally, the version of MAGIC used takes a highly simplified approach to N dynamics, and additionally N deposition is assumed to remain constant in forecast scenarios. A recent modification of the model includes a more detailed representation of N dynamics, and use of this model would improve the reliability of acidity predictions (Wright *et al.*, 1998). This version of the model, however, requires additional data on soil C:N ratios, which are not currently available for all the Critical Loads sites. Further data collection will, therefore, be needed before this more detailed model can be applied.

Conclusions

As a first attempt to apply a dynamic model of surface water acidification, MAGIC, to sites on a national scale in the UK, this study provides reasonably encouraging results. Out of 1573 surface water locations sampled during a survey of the UK, 1027 had sufficient data for the model to be applied, of which a total of 698 were successfully calibrated. Change in surface water chemistry at these sites has been simulated from 1850 to the present day, and forecast to 2050 on the basis of reductions in sulphur deposition agreed under the Second S Protocol.

Model results indicate differing regional trends. The

most severe present-day acidification occurs in parts of northern England, where deposition levels are high. Due to the limited number of successful calibrations in this region, it is difficult to predict future trends with confidence. From the results available, however, it appears that significant recovery should occur in response to the Second S Protocol, but that a considerable number of sites may, nonetheless, remain severely acidified to 2050. In contrast, three regions with moderate levels of deposition, Wales, Galloway and Dartmoor, which also have a significant number of acidic surface waters, are predicted to exhibit far less recovery under this emission scenario. In the low deposition region of northern Scotland, most sites have not acidified greatly, and so predicted future changes are small. For individual regions, average predicted ANC recovery ranges from 19% to 36% of modelled historic acidification, and for the country as a whole the average is just 27%.

The consistency of results at a regional scale implies that the model captures the dominant processes successfully. There are, however, limitations to the application of MAGIC at the spatial scale considered here. The large number of sites considered requires that much of the input data be estimated from existing databases rather than measured at individual locations, thereby increasing uncertainty in the simulations. Uncertainties in the estimation of soil properties has created difficulties in the modelling of some catchments, notably in acid-sensitive areas of England and Wales. The single surface water chemistry sample collected at each site also limits accuracy, in that it represents a crude approximation of annual mean chemistry. The effects of antecedent seasalt inputs on sites in north-west Scotland and the Lake District generate a particular problem. In applying this type of model, there is necessarily a trade-off between the accuracy of input data and the extent of spatial coverage. For interpretations to be made on a regional or national scale, a certain reduction in the precision of model parameterisation is unavoidable. The net impacts of these parameterisation errors at individual sites are minimised, however, when results are considered on a regional scale.

There is significant potential for improving and extending this model application. Improved input data estimation would allow the model to be applied to existing surface water sites with greater precision, and increased spatial coverage of soils data (notably for Northern Ireland) would permit additional sites to be calibrated. Inclusion of N dynamics and deposition changes will now be possible using the modified version MAGIC 7, and further improvements may be possible through consideration of land-use impacts such as forestry and agriculture.

Given the scale of the Critical Loads survey, it would not be practicable to resample all sites to improve representation of annual means. However, targeted resampling of sites believed to have been impacted by seasalt inputs during the original survey might improve the accuracy of

model simulations at these locations and increase the number of sites that could be calibrated. Sampling of soils in catchments where estimates for soil base status appear incompatible with surface water chemistry might also improve the number of calibrations in important acid-sensitive areas.

Finally, the Critical Loads survey and model application have identified the Pennines, Lake District and North York Moors as particular regions of concern, both in terms of current acid status and incomplete future recovery. Further, more detailed regional surveys and model applications in these relatively under-researched areas would greatly improve knowledge and understanding of what appear to be the most severe instances of acidification in the UK.

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