8 Summary and Conclusions

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8.1 Atmospheric deposition and the impact on UKAWMN sites (1988-1998)

The ultimate aim of emissions reduction policy is to achieve improvements in target environments damaged by the effects of atmospheric deposition. Emission reductions on a national and international level have resulted in a major decline in SO_2 concentration and S deposition in urban and rural areas in central and south England. However, the target environments of concern for the UKAWMN are the acidified freshwaters which are mostly located in more remote parts of the UK. In order to test whether these ecosystems have benefited from implemented policy, a series of functional links, from emissions reduction, through deposition reduction, to the recovery of water chemistry and finally aquatic biota, must be demonstrated. Each link has been discussed in the course of this report, and is summarised below.

Have reductions in anthropogenic emissions led to a reduction in acid deposition in the UK over the past decade?

Undoubtedly yes. Over the period 1986-1997, sulphur emissions reductions of 55% have almost been matched by a 50% reduction in sulphur deposition for the UK as a whole. However, smaller declines in emissions of NO_x are not reflected in deposition trends. In some remote regions NO_3 deposition appears to have increased slightly.

Do we observe reductions in sulphur deposition in the regions with acid sensitive freshwaters?

Nationally, there has been a disproportionate decline in dry, relative to wet, deposition. Substantial reductions in both wet and dry xSO_4 and H^+ concentrations have occurred at sites within 100 km of major emissions sources, and particularly those in the east Midlands and Yorkshire. This has had a major effect in the Pennines area where freshwaters are believed to be some of the most impacted in the entire UK. Sensitive areas at intermediate distances from sources, including mid-Wales and the Lake District have experienced smaller, but still measurable, declines in xSO_4 deposition. However, the majority of UKAWMN sites lie beyond these regions, to the west and north, where rainfall is high and SO_4 deposition is predominantly in wet form. Here, downward xSO_4 trends during the last ten years have been very small and only detectable using regional analysis. The signal at these sites appears to be swamped by noise resulting from climatic variability. Reductions in xSO_4 deposition have therefore occurred in all areas, but rates of reduction are geographically skewed, being virtually undetectable in the more remote regions, including north Wales, and southwest, central and northwest Scotland.

Has deposition reduction led to declines in acid anion concentrations in UKAWMN freshwaters over the last decade and over longer time scales?

Large declines in xSO_4 concentrations have been recorded at Old Lodge (southeast England) and the River Etherow (Pennines). Smaller, but still significant declines in concentration have occured at Lochnagar (northeast Scotland). The effects of small reductions in the deposition flux of SO_4 from non-marine sources at other sites could be masked by noise from inter-annual variability and problems associated with the use of a fixed ratio of SO_4:Cl to correct for sea-salts, since SO_4 is believed to be retained relative to Cl after sea-salt deposition episodes. For the majority of sites therefore, there is little indication of declining xSO_4 concentration over the monitoring period. However, data from longer time series for sites in mid-Wales, and southwest and central Scotland, show that there has been a considerable reduction

in xSO_4 concentration from the early 1980s to the present. It is likely that sizeable deposition reductions coincident with a sea-salt correction effect, were responsible for a large decline in xSO_4 concentration at Scottish sites in the mid-1980s.

Although there is spatial correlation between NO_3 deposition fluxes and surface water concentrations, inter-annual variation in NO_3 concentration appear to primarily reflect climatic differences between years.

Have improvements in pH or alkalinity been observed at sites where acid anion concentrations have declined, or elsewhere?

At the River Etherow and Old Lodge, the only sites which have experienced large decreases in xSO_4, there is little evidence of chemical recovery over the interpretative period. The River Etherow exhibits considerable flow-dependent temporal variability in acidity, so detection of an anticipated small overall improvement is particularly difficult here. However, it appears that chemical recovery at both the Etherow and Old Lodge may have been slowed, as a result of base cation declines partly offsetting declines in acid anions. Similar observations of delays in recovery have been made in the United States and Scandinavia, although for the latter it appears that increases in base cation concentrations and alkalinity are now underway. For Lochnagar, the decrease in xSO_4 has been outweighed by an even greater increase in NO_3, and as a result this site has continued to acidify. The longer term datasets available for a limited number of sites provide a more encouraging perspective. Relatively large reductions in xSO_4 observed in the mid-1980s were associated with increases in pH in most cases.

Seven UKAWMN sites do show positive linear trends in pH and/or alkalinity. However, these sites are mostly in areas where deposition reductions have at best been very slight, and most show little evidence for downward trends in total acid anion concentrations. It is therefore possible that most observed trends primarily represent an overall decline in the combined effects of sea-salt deposition and high rainfall, both of which can temporarily enhance acidity. The 1988-1998 period appears at most only to encompass one climatic cycle with regard to these effects. Further years of monitoring are therefore essential before the full extent of their influence can be quantified and statistically removed, so that any underlying deposition related trend may be identified.

Are changes in acidity in UKAWMN sites reflected in aquatic biology?

At two sites, Llyn Llagi and Loch Chon, improvements in pH are matched by linear trends in epilithic diatoms and macroinvertebrates which are indicative of improved conditions. For Llyn Llagi, comparisons between the diatom assemblage of sediment traps (recent) and a sediment core (the past) provide convincing evidence that biological recovery, at least at the lowest trophic level, is underway at this site. This recovery has seen the re-establishment of a similar diatom flora to that lost in the latter stages of acidification. Whether continued improvement might eventually lead to a return to the pre-acidification flora is of course impossible to predict and will only be ascertained by continued monitoring. Similar indications of reversal are evident for Loch Chon, but here it is also possible that the observed trends are at least in part driven by climatic influences.

Inter-annual variation in species assemblages at lake sites which do not show trends, also appears to reflect inter-annual variation in pH. These results are perhaps not surprising given the well established dependence of the diatom flora on pH, but do suggest that this community will respond rapidly, if, when and where real chemical “recovery” occurs.

For the streams, there is strong, although indirect, evidence from rainfall data and flow/pH relationships, that the diatom community reflects mean summer acidity. At sites such as the River Etherow, which undergo large variation in pH depending on the proportional contributions of surface run-off and base-flow, very dramatic improvements in pH at high flow would be necessary for any effect to be observed in the

summer diatom samples in the near future. The other primary producer group, the aquatic macrophytes, provide no indication of response to temporal variation in pH.

Linear trends in macroinvertebrate communities, which were identified for 11 sites, (mostly lakes) can also be linked to variation in acidity, although in this case it is unclear whether there is any causal relationship or whether biology and chemistry are simply co-variable. It is likely that these trends reflect a general decline in the intensity and/or duration of acid episodes resulting from the combined effects of enhanced sea-salt deposition and high rainfall over the period of interpretation. If this is the case, and given the evidence from the longer term records of a few sites, that emissions reductions have led to a gradual reduction in severity of spring acidity since the early 1980s, we should expect to see a gradual (although non-linear) improvement in the lake fauna with time. Alternatively however, the lake fauna may primarily be affected by other climatic factors including the frequency and magnitude of lake level oscillations or by inter-annual differences in winter temperature. It is therefore crucial that experimental work is undertaken, in conjunction with continued monitoring, to address these issues.

The apparent sensitivity of the lake macroinvertebrate community to climatic conditions in spring, raises the question as to whether autumn sampling would provide a less "noisy", and therefore more easily interpretable, record of "recovery" in response to chemical improvements. Similarities in the temporal variation of species richness amongst stream sites, including those which show no relationship between pH and flow, suggest that physical flow conditions are likely to have had a major influence over the monitoring period.

Temporal variation in trout density and condition factor data show less coherence between sites. Assessment of population statistics for fish are complicated by their highly mobile nature. Consequently the relative importance of recruitment, mortality and up- or down-stream migration is very difficult to quantify. Mobility therefore represents another source of noise and lengthens the period of monitoring which is necessary for recovery trends to be identified. There is a suggestion from UKAWMN data that density differences between sites may be related to labile Al concentrations. The most striking within-site relationship identified concerns a significant increase in trout density at Old Lodge which mirrors the reduction in labile Al over the same period. These data suggest that, for sites where healthy populations are already present in better buffered waters downstream, reductions in labile Al might induce rapid upstream migration. To date, temporal relationships between trout density or condition factor and chemistry for most other sites are insignificant.

8.2 Further observations

In addition to answering the primary questions regarding environmental response to the changing acid emission regime, the considerable time series of data collated by the UKAWMN provides new insights into environmental processes in upland freshwater catchments. These are often of direct relevance to the overall aims of the Network, but are also broadening our understanding of the influence of climate variability, and the potential influence of long term climate change on upland freshwaters. The following points summarise the main findings of recent data analysis.

- Increases in NO_3 at Lochnagar, Round Loch of Glenhead, Loch Chon and the River Etherow suggest increasing N saturation of these catchments, although they may also have been influenced by small increases in NO_3 deposition. Concentrations are expected to continue rising unless substantial reductions in deposition are achieved. At other sites, any saturation-related increases that may be occurring are obscured by other sources of variation, including episodicity and seasonality. Inter-annual variations in NO_3 have also been linked to climate; an inverse relationship has been demonstrated between winter temperature and spring NO_3 maxima, and is believed to reflect variations in the North Atlantic Oscillation (NAO).

- Dissolved Organic Carbon (DOC) concentrations have increased strongly in virtually all monitored regions of the UK; highly significant rising DOC trends have been identified at nineteen of the twenty-two UKAWMN sites, with concentrations at six sites having doubled or more during the last decade. The biological impacts of these increases are likely to be varied, including reduced light penetration due to increased water colour which could restrict the depth of plant growth; reduced penetration of potentially damaging UV-B radiation; and reduced toxicity to fish under acidic conditions due to organic complexation of aluminium. It is not currently possible to identify a definite mechanism for DOC increases, or therefore to predict whether they will continue into the future. However, the most the most probable hypothesis is increased microbial decomposition of soil organic matter resulting from increasing summer temperatures. Under a scenario of rising global temperatures, therefore, DOC and colour levels in upland waters may be expected to increase further.

- Inter-annual variability in levels of sea-salt deposition has been identified as a major cause of chemical variation in the UKAWMN dataset. The majority of UKAWMN sites lie within 50 km of western or southern coasts, and receive large sea-salt inputs during westerly or south-westerly frontal storms. The frequency of these storms has been shown to vary substantially from year to year, with maxima associated with high winter values of the NAO Index. Marine ion concentrations at near-coastal sites have consequently shown highly consistent cyclical variations, with a major peak during the high NAOI 1989-1991 period. Cyclical variations have also been observed in non-marine cations, including H^+ and labile Al which are believed to result from cation exchange processes associated with the sea-salt effect. It is proposed that a parallel process of marine SO_4 adsorption and desorption may also operate, leading to cyclical fluctuations in calculated xSO_4 which are unrelated to variations in pollutant S inputs.

- The identification of climatically-driven cyclicity in xSO_4, NO_3, acidity, and other important measures of surface water quality, has major implications for detection of recovery related trends, applicable both to the UKAWMN and to other monitoring programmes. Cyclical variations have the potential either to mask underlying anthropogenically-driven trends, or to generate apparent trends as a result of natural processes. Since these variations appear to operate at approximately decadal timescales, there is clearly a need to monitor over longer time periods in order to fully characterise the impact of anthropogenic factors on surface water quality.

8.3 Assessment of Network Performance

The UKAWMN has been operating for almost 12 years. Over this period it has maintained high standards of sampling and analysis. With very few exceptions chemical and biological sampling has been undertaken with consistent frequency, while minimal personnel changes have helped to ensure that sampling protocols have been maintained through time. Water chemistry laboratories have participated regularly in AQC schemes at both national and international level and have been shown to maintain consistently high standards.

There is little evidence of catchment disturbance at the majority of sites. Problems have arisen at Loch Coire nan Arr, where the installation of a dam and subsequent management of the water level has had adverse biological impacts. At forested sites, considerable clearance and replanting has been instigated at Allt na Coire nan Con, and since the end of the interpretative period, at the Afon Hafren. Forestry at other sites is approaching maturity and felling programmes are expected to be implemented soon. The River Etherow appears to be occasionally influenced by road-salt and survey stretches have also been subject to vandalism. Despite this, the water chemistry record very clearly demonstrates the reduction in xSO_4 and non-marine cations which have resulted from the large decrease in xSO_4 deposition, and the site continues to provide data which are representative for the area.
Sediment traps, which were initially deployed in

1991 with varying levels of success of retrieval in the following year, have now been operating well in all lakes for several years. Trap samples, in conjunction with sediment cores taken at the onset of monitoring, are now providing the most powerful evidence of biological recovery (or inertia) at UKAWMN lakes.

Generally therefore, UKAWMN sites continue to perform well and all are providing high quality data. The extent to which between-site relationships in temporal variation have been used in the analysis for this report underlines the important contribution each site lends to the strength of the whole Network.

8.4 Recommendations

In light of the findings of this report we would recommend:

Continuation of monitoring for the following reasons:

- In common with substantial numbers of other acid-sensitive freshwater catchments in the UK, the majority of UKAWMN sites have clearly acidified, and remain in a damaged state. Most show little evidence of chemical or biological recovery to date and such recovery will only be identified by ongoing monitoring.

- Acid emissions reductions continue to be implemented and deposition of total acidity should continue to decline for the foreseeable future for the UK as a whole. However, the extent to which the impact of future declines on freshwater ecosystems will be observed in the more remote acid sensitive areas is unclear and this can only be verified by further monitoring.

- Deposition of NO_3 may have increased in some remote areas and may continue to do so. Continued monitoring is the only method of assessing the potential impacts.

- Acid pollutants stored in catchment soils are likely to be causing lags in dose-response relationships, while future NO_3 saturation and consequent N breakthrough is possible for some catchments. Lags are also likely between chemical improvements and biological recovery, particularly for organisms further up the food chain. These effects may not be observed for some time yet but will only be verified by monitoring.

- Water chemistry and biology of UKAWMN sites demonstrates marked inter-annual variability, a considerable proportion of which can be attributed to climatic variation. Given the amplitude of "noise" relative to expected rates of recovery, longer time series are necessary to identify underlying trends.

- The UKAWMN has the potential to provide valuable information regarding the impact of possible long term climatic changes on upland freshwater systems. Widespread rising trends in DOC suggest that such changes may already be affecting UKAWMN sites.

- The UKAWMN database represents an unparalleled, high quality and continuous integrated time series for acid-sensitive freshwaters in the UK. As the datasets continue to develop their scientific value continues to increase.

- UKAWMN data are integral to other national (i.e. ECN) and international (i.e. UNECE ICP) monitoring networks.

The UKAWMN would benefit from the following enhancements:

1) Increased frequency of chemical sampling during winter months to better define the extent and intensity of sea-salt and flow driven episodes (ideally to weekly for streams and two weekly for lakes).

2) The inclusion of further biological groups to enhance our understanding of ecosystem level responses. Most importantly, zooplankton samples should be collected at least annually but preferably quarterly. An additional macroinvertebrate survey each Autumn may reveal more stable trends in fauna with time, given the apparent sensitivity of spring samples to climatic variation.

3) More rigorous assessment of transparency by measurement of absorbtion of water samples at multiple wave-lengths. Partitioning of DOC into molecular weight ranges by ultra-filtration, so that the causes of increases (should they continue) be better understood.

4) Continuous measurement of water temperature (including temperature profiles in lakes) using self contained thermistor-dataloggers to enhance our understanding of links between climate and aquatic biology.

5) The collection of additional water, plant and sediment samples for metals analysis, and particularly for Cd, Hg, Pb, Zn and Cu. This would help to address contemporary international directives for this group of transboundary pollutants.

6) The monitoring of an additional site in the locality of Loch Coire nan Arr, which is threatened by water level management, so that this low deposition area will continue to be adequately represented in the future.

7) The monitoring of another close-to-source site, in the east Midlands or southern Pennines, so as to increase representation in areas where S deposition is declining most rapidly.

8) Closer practical links, particularly between the UKAWMN and the UK Acid Deposition Network. Particular areas of collaboration should include investigations into the dose-response relationships for SO_4 and Cl at specific catchments, and other interpretative analysis of temporally coterminous datasets.

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