APPENDIX 2

Draft manuscript:

Visual Presentation of Uncertainty in Critical Load Exceedances Across Wales

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Visual Presentation of Uncertainty in Critical Load Exceedances Across Wales

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***Abstract*.** Critical loads and their exceedances were used as the basis for the negotiation of the Gothenburg Protocol and the National Emissions Ceilings Directive to reduce emissions of sulphur and nitrogen by 2010. Since emissions have already been significantly reduced the associated cost in further emission reductions is high. Hence the policy maker needs to know and understand the uncertainties in critical loads and their exceedances, upon which any future abatement policy would be based. In this paper the effect of using uncertain deposition data on the critical load exceedance calculation is presented. Deposition data from the Hull Acid Rain Model (HARM) has been used in this analysis. Deposition uncertainty estimates have previously been calculated for each 10km grid square in Wales using Generalised Likelihood Uncertainty Estimation methodology (GLUE). The critical loads data was not varied in this analysis. Distributions of critical load exceedances were constructed from the uncertainties in deposition estimates. Four separate methods of visually presenting the uncertain exceedance data to the policy maker are presented. These methods allow the identification of areas subject to different levels of risk.

1 Introduction

The underlying notion of the critical loads concept is that of a dose response function - a sensitive element is specified for an ecosystem and the critical load is defined as the level below which significant harmful effect does not occur. Critical loads are calculated to assess the impacts of those pollutants, among others, responsible for acidification and eutrophication. Sulphur deposition arises from power stations and industry and contributes to acidification. Oxidised nitrogen comes from vehicles, power stations and industry whilst reduced nitrogen arises from agriculture. Nitrogen compounds can enhance the acidity effects of sulphur and leads to eutrophication; that is excess nitrogen as a nutrient. Pollutant deposition is compared with the critical load function to determine the amount of excess deposition above the critical load, termed the critical load exceedance. National exceedance data are mapped, and regional and national statistics derived, in a variety of ways to allow the policy maker to assess the likely impact and effectiveness of possible control or abatement measures. National critical loads data are submitted to the Coordination Centre for Effects (CCE) which assesses how national air pollution abatement measures can reduce these risks to ecosystems in Europe and supports effects-based air pollution reduction policies under the UNECE LRTAP.

Current policies have assumed model estimates of critical load exceedances are accurate. However as time has gone on it has become more costly to reduce air pollutant emissions to achieve environmental benefits. This has driven the European critical load community to attempt to assess the uncertainty in exceedance calculations and present this information to the policy maker. Best and worst-case maps showing grid cells in Wales which are always exceeded with high and low deposition scenarios are given in Gascoigne *et al.* 1999. Maps showing areas subject to significantly different levels of exceedance and probability of exceedance within a region of Sweden were introduced by Barkman *et al.* 1999. Suutari *et al.* 2001 showed maps of the percentage of protected ecosystem in Europe using 50, 95 and 5 percent probability. Probablistic exceedance plots showing the probabilities associated with different estimates of area exceeded in Finland are given in Syri *et al.* 2000.

The aims of this study were to:

- Estimate the effects of uncertainty in calculated exceedances using deposition uncertainty information only (uncertainties in critical loads data was not considered in this analysis)
- Develop methods for the visual presentation of uncertainties in critical load exceedances, to effectively communicate information on uncertainties to both scientists and policy makers.

Deposition only has been varied in this study as it has been shown nationally that the critical load exceedance calculation is more sensitive to deposition than critical loads (Defra report). Although the same approach can be applied to exceedances of nutrient nitrogen critical loads it has only been applied to acidity critical loads in this work. Wales was used as a case study as it is a heavily exceeded region which contains a range of sensitive ecosystem types. Analysis of a variety of different exceedance endpoints has been undertaken.

Thousands of realizations of the exceedance calculation were produced for this work. It is obviously impossible to present the policy maker with each realisation as a separate set of statistics or map. There needs to be some way to express the additional information that these multiple realisations provide without confusing the user. The product also needs to be visually distinct from the traditional way of expressing exceedances so it is obvious to the viewer that they are reading different information. Methods of conveying the uncertainty information are developed which are similar in some ways to the methods described by Gascoigne *et al.* 1999, Barkman *et al.* 1999 and Suutari *et al*, 2001.

2 Methods

2.1 Input data

2.1.1 Critical loads data

In February 2003 the national critical loads of acidity and nutrient nitrogen were updated for a number of Biodiversity Action Plan broad habitat types sensitive to acidification and eutrophication. Acidity critical loads are mapped for the following terrestrial habitats: calcareous grassland, acid grassland, dwarf shrub heath, bog, montane, managed coniferous woodland, managed broadleaved woodland and unmanaged (coniferous and broadleaved) woodland. Critical loads are calculated for systems at steady-state. Information on the methods used to map and calculate UK critical loads can be found in the UK Status Reports on the UK National Focal Centre web site (http://critloads.ceh.ac.uk).

The analysis presented in this paper focuses on the acidity critical loads data for Wales only. The total area of acid sensitive habitats mapped for critical loads in Wales is estimated as 6 745 km^2. National ecosystem maps can be found in Hall *et al.* (2003a).

2.1.2 Deposition data

The Hull Acid Rain Model (HARM; Metcalfe *et al.,* 1995a, 2001) was used to provide uncertain deposition estimates for this analysis. It models deposition data at 10km resolution and includes deposition estimates of wet and dry sulphur, oxidised and reduced nitrogen. HARM has been used extensively by the UK Department of the Environment, Foods and Rural Affairs (DEFRA) to inform policy making decisions with regard to reducing deposition of acidifying pollutants (RGAR, 1997; NEGTAP, 2001) and minimising ecosystem damage as expressed by exceedances of critical loads. It is currently the only UK national deposition model for which estimates of uncertainty have been modelled on a grid cell by grid cell basis.

Distributions of deposition values were generated from multiple simulations using HARM within the Generalised Likelihood Uncertainty Estimation (GLUE) framework of Beven and Binley (1992). A full description of the work is presented by Page *et al.* (2003). The GLUE methodology recognises that, given the uncertainties and errors within model structyre, boundary conditions and observed data, many different combinations of model parameters and/or model structures will be equally acceptable descriptors of the modelled system. Hence GLUE does not seek to obtain a single optimal parameter set for a given model structure, but rather many parameter sets that are '*behavioural*' in describing the system based upon their fit to observed data.

The multiple behavioural simulations used to generate the deposition values used within the study were obtained by conditioning HARM estimates on site-specific wet deposition observations at 25 sites across Wales (Stevens *et al.* 1997; Reynolds *et al.* 1999) and estimates of 'reasonable' wet to dry deposition ratios (NEGTAP, 2001). One hundred thousand simulations were run using parameter sets generated by Monte Carlo sampling of pre-specified parameter ranges. From the 100,000 simulations 2101 were accepted as 'behavioural' and were given a likelihood weighting bases on their performance across all sites considered. The 2101 behavioural parameter sets were used to simulated deposition fluxes to the 261 10 km Welsh grid squares. For each grid square a likelihood-weighted cumulative distribution function was produced from which 5th , 50th and 95th percentiles of deposition distribution were obtained.

2.2 The exceedance calculation

The amount of excess deposition above the critical load function is called the exceedance. It provides an indication of the likely potential for harm. When exceedances are being calculated it should be remembered that the critical loads and deposition data are at different spatial scales. The 1km critical loads data (for each habitat) is compared with the deposition. When the exceedance information is being conveyed the following maps are produced:

1. Exceedance of critical loads for individual ecosystems at 1km resolution.
2. Exceedance of percentile critical loads (this enables the calculation of critical loads for combined habitats and can also be used to aggregate the data to a coarser resolution)

In most practical cases the policy maker is interested in combining all the data to produce for example an "acidity critical load exceedance map of the UK" without further specifications. In order to aggregate the data for all habitats the exceedance information is combined with habitat area to calculate:

1. The total area of sensitive habitats for which the critical load is exceeded.
2. The accumulated exceedance which integrates both the area of habitat exceeded and the magnitude of the exceedance (AE (eq/year) = exceedance (keq/ha/year) * exceeded area (ha)).

The area exceeded and accumulated exceedance information can be presented to the policy maker in two ways:

1. Statistics of exceeded area or AE can be derived for each habitat separately but are usually summed across grid squares to give regional or national statistics.
2. Area exceeded and AE maps are generally derived for all habitats combined and aggregated to the same resolution as the deposition data.

2.3 Uncertainty of critical load exceedance

The aim of the analysis was to assess the uncertainty in critical load exceedance from uncertainty in deposition estimates and to present this information to the policy maker in a visual form.

Two methods of calculation were used and the results of the analysis were presented and interpreted in various ways.

1. Area exceeded and accumulated exceedance is calculated for high (95^{th}), low (5^{th}) and medium (50^{th}) percentile deposition data for each grid square. Statistics are calculated for individual ecosystems and maps of area exceeded for combined ecosystems are presented at the resolution of the deposition data.
2. Exceedances are calculated for all 2101 predicted deposition scenarios for every 1km grid cell. The distribution of critical load exceedances are presented in the form of cumulative density functions (CDF) and maps defining separable classes and probability of exceedance for 1km grid cells for a selected ecosystem type.

3 Results and discussion

Of the 261 10 km grid squares in Wales only 250 of them contain habitats sensitive to acidification. Hence 11 squares are mapped as white squares indicating that these squares contain no habitats which are sensitive to acidification.

3.1 Results using deterministic data

Exceedances were calculated and mapped using the HARM deterministic data. The deterministic case refers to the model run using the nominal input parameters (ie no uncertainty incorporated). Table 1 shows the statistics for each broad habitat separately for area exceeded and accumulated exceedance. The percentages in brackets give the percentage of the total habitat area that is exceeded. 71% of sensitive ecosystems in Wales are exceeded using the determinstic data. The accumulated exceedance is 339670 keq year^{-1}. Figure 1 shows the area exceeded and accumulated exceedance maps. These maps are at 10 km resolution and show the results for all broad habitats combined. 211 10 km squares are exceeded leaving 39 not exceeded.

3.2 Exceedance estimates using 5th, 50th and 95th percentile deposition

3.2.1 Statistics

The calculated exceedances using HARM 5th and 95th prediction bounds are compared to those calculated using the deterministic data (Table 1). These scenarios can be thought of as best case (5th) and worst case (95th) deposition scenarios. Table 2 gives the percentage deviations from the deterministic data for each habitat separately and for all habitats combined. Table 2(a) gives the percentage change in area exceeded and table 2(b) the percentage change in accumulated exceedance. The area exceeded ranges from about 51% to 89% of sensitive ecosystems exceeded. The accumulated exceedance ranges from about 104 000 keq year^{-1} to approximately 878 000 keq year^{-1}. The percentage deviations for area exceeded and accumulated exceedance are largest for woodland habitats and smallest for bog and montane habitats. The percentage deviations are larger for accumulated exceedances than area exceeded. This is because the accumulated exceedance also takes into account the magnitude of exceedance.

We can make the assumption that if we protect those ecosystems exceeded using the 95th percentile deposition (high deposition scenario) we are protecting all areas at risk of acidification, this gives an approximately 25% increase in the area exceeded above the deterministic data. If we again take a conservative interpretation of risk this leads to an approximately 150% increase compared to the deterministic approach.

3.2.2 Maps

An alternative view is to consider the spatial aspect of uncertainty. Percentile ecosystem exceedance in Wales is computed from the percentile deposition for every grid square. The results for area exceeded are displayed in Figure 2 and for accumulated exceedance in Figure 3. Figures 2(b) and 3(b) display the results from the deterministic calculation. "Worst case" scenarios are shown in figures 2(a) and 3(a); these show the areas of Wales that are exceeded with the 5th prediction bound deposition scenario; these are the areas we can be certain are at risk. "Best case" scenarios are shown in figures 2(c) and 3(c); these show the areas of Wales that are exceeded with the 95th prediction bound deposition scenario; these are the areas we should be protecting to be certain we are protecting all the sensitive ecosystems. These maps allows us to assess a confidence level for ecosystem exceedance, i.e. figures 2(a) gives the 95th confidence interval of exceeding less than or equal to the specified area in each 10km grid square in Wales and figure 2(c) the 5th confidence interval.

In an ordinary critical loads assessment the results are usually divided into arbitrary classes when producing maps (Figure 1). An uncertainty analysis, however, makes it possible to divide the results into levels of risk/exceedance. Three levels of exceedance may be identified using the percentile deposition data: Non exceedance is assumed to be all those grid squares that are **not** exceeded using 95th percentile deposition, and exceedance as those grid squares exceeded using 5th percentile deposition. This methodology tells us that we are confident that some cells are always exceeded and some never exceeded but those in the middle category are the interesting ones. All squares which "flip" from non exceedance to exceedance between these two extremes are classed as uncertain (ie those squares that are not exceeded at 5th percentile deposition but are at the 95th percentile deposition). These results are shown in Figure 3. The legend also shows the same data interpreted as risk ie acceptable, uncertain and unacceptable risk. The dark green indicates that the grid cell has not been exceeded at high deposition scenarios (95th percentile), the dark red indicates that the grid cell is exceeded at low deposition scenarios (5th percentile) and the light grey indicates that the grid square is not exceeded at the 5th percentile but is exceeded at the 95th percentile.

There are 79% of the sensitive 10km grid squares in Wales are in the unacceptable level of risk class; 7.6% in the acceptable level of risk class and 13.6% in the uncertain class.

It should be remembered when interpreting these maps that the critical loads data is at 1km resolution and contains critical loads data for up to 9 different ecosystems. Hence when a 10km square is shown as non exceeded it means that all the 100 1km grid squares contained within that grid square are not exceeded for any of the ecosystems contained within them. To investigate the effect of a change of scale the same map was reproduced at 5 km resolution (figure 5). This produced 75% of 5km grid squares in the unacceptable level of risk; 7% in the acceptable level and 18% in the uncertain class. To investigate the effect of looking at one ecosystem at a time within a grid cell coniferous woodland was chosen. This changed the results quite significantly so that 28% of grid squares were in the acceptable level of risk; 37% in the unacceptable and 35% in the uncertain.

Obviously, more sophisticated maps can be produced delineating levels of risk based on the deposition percentiles. For example, one of the grid cells may be exceeded at the 95th percentile deposition but not at the 75th percentile deposition. This means that the critical load is only exceeded at high deposition scenarios and hence has a relatively low risk of exceedance. Conversely a grid cell that is not exceeded at the 5th percentile but is exceeded at the 25th percentile has a relatively high risk of exceedance, ie it is exceeded at quite low deposition scenarios.

3.3 Presentation and interpretation of distribution of exceedance

The above methods presented probabilities in terms of area exceeded and accumulated exceedance or in terms of whether a grid square was exceeded or not exceeded. An alternative method which directly incorporates knowledge of the magnitude of exceededance is by analyzing the distribution of the size of the exceedance (positive or negative). Since the critical load data is at 1km resolution and is ecosystem specific the critical load exceedance has also to be analysed at 1km for individual ecosystems. The analysis was performed for an illustrative habitat type, in this case coniferous woodland. This ecosystem type was chosen as it has good spatial coverage over Wales.

3.3.1 Cumulative Distribution Function (CDF)

The red line shown in Figure 7 was formed from the distribution of exceedance values using all the results from the GLUE simulations for a 1km grid square of coniferous woodland (OS coordinates xx xxx, area x km^2). The results were ranked from smallest to largest. Each was assigned a probability according to the equation:

$$P = r / (N+1)$$

Where r = rank and N = number of simulations. In this way, one obtains the cumulative distribution function. The 5th percentile has a value of -0.71, the 50th percentile -0.388 and the 95th percentile -0.71 keq $year^{-1}$.

The information obtained from this analysis can be used to guide decisions following Hammonds *et al.* 1994. For example, if the CDF of exceedance for an individual grid cell has a 5% lower confidence limit that is above zero, then it is likely that the grid cell is exceeded. If the 95% upper confidence limit is below zero, it is likely that the grid cell in not exceeded. If the 95% upper confidence limit is above zero, but the 50th percentile is below zero further study should be recommended on those parameters that dominate the overall uncertainty. However, if the 50th percentile is above zero, further study may still be recommended, but under some circumstances one may opt to consider that critical load is exceeded and deposition needs to be reduced depending on the cost-effectiveness of measures for risk reduction. In this case we can be certain that the coniferous woodland contained within this 1km grid square is not at risk of acidification.

3.3.2 Data classification

The CDF and confidence limits shown above is a good way of presenting the uncertain exceedance data for a single grid cell. However when we want to produce maps across a larger spatial extent this method is not feasible unless the critical loads data was aggregated using percentile critical loads and exceedances. This is discussed further in the conclusions and further work section.

Another way to present this data would be to produce colour-coded maps which classify this data into different levels of risk of exceedance. To some extent any classification scheme we adopt will be arbitrary. One method would be to use the method of Hammond *et al.* 1994. Another would be to base the classification on the mean and standard deviation of each grid cell. In this method it is proposed to find the mean value for each of the grid cells and calculate the range two standard deviations above and below the mean value. If this lower end of the range is greater than zero the grid cell will be classed as exceeded, if the higher end of the range is less than zero the grid cell will be classed as not exceeded and all other grid cells are classed as uncertain. In figure 8, grid cells are mapped using this classification method. Most of the grid cells in Wales fall in the uncertain category. Further categories could be defined by using intervals at either 1, 0.5 or 0.25 standard deviation.

3.3.3 Probability of exceedance

The cumulative distribution in figure 7 can be used to calculate a probability of exceedance (probability of exceedance greater than zero) of 2.4%. The blue line in the figure shows the normal distribution curve fitted to the exceedance distribution. The exceedance distributions for each 1km grid square were assumed to be normally distributed. By transforming the exceedance data using the calculated mean and standard deviation to give a standard normal distribution the probability of exceedance was calculated for every 1km grid cell in Wales.

Figure 9 show the probability of exceedance mapped as a continuous distribution. Those grid cells in the 0-5% probability of exceedance range are unlikely to be exceeded: those in the >95% probability of exceedance range are likely to be exceeded and those in the intermediate ranges may be both exceeded and not exceeded.

The areas included in the legend of Figure 9 refer to the area of coniferous forest that is exceeded within those probabilities. Summing these areas give 1 030 km^2 which is the total area of coniferous woodland in Wales. This emphasizes an important feature of the probability exceedance map: that there are no areas that are fully protected according to the critical load concept, i.e. non exceeded, and that only probabilities of exceedance exist.

If we wanted to be 95% certain we were protecting all the areas at risk of acidification we would disregard that area with a less than 5% probability of exceedance to give 900 km^2 of exceeded area. On the other hand if we were willing to accept just a 5% probability of exceedance only 130 km^2 of coniferous forest would be exceeded.

4 Conclusions and Further Work

A methodology has been presented that uses sulphur and nitrogen deposition uncertainty predictions (using GLUE methodology) to assess the uncertainties in critical load exceedance.

Distributions of critical load exceedance constructed from the uncertainties in deposition estimates (critical loads were not varied) produced distributions of critical load exceedances for every grid square in the United Kingdom (at various resolutions). Various methods of visualising these outputs were applied to the distributions.

Uncertainties in deposition estimates have a substantial effect on exceedance calculations. Using 5^{th} and 95^{th} prediction bounds of 1995 deposition uncertainty suggests the uncertainty in area exceeded could be between -10 and +25% (Table 2) of the nominal value. In relation to AE, the 5^{th} and 95^{th} prediction bounds suggests that the uncertainty may be even greater (eg between -46 and +159% of the value derived using the nominal data). Mapping the results using this data allowed us to predict the 5^{th} and

95th confidence limits for exceeded area and accumulated exceedance. It also allowed us to assess which 10 km grid squares are in acceptable, unacceptable and uncertain level of risk classes. At 10km resolution most of the grid squares where considered to be at unacceptable level of risk of exceedance. The same analysis carried out at the 5km scale showed that the percentage of uncertain squares increased slightly with an increase in resolution. However analyzing the coniferous woodland exceedance data alone dramatically reduced the percentage of uncertain grid squares. Since we might expect the critical load exceedance distributions to be similar for a single ecosystem type within a 5km grid square it is not surprising that this reduces the uncertainty.

The developed methods to visualise uncertainty in critical load exceedance calculations can be used to identify areas with different level of risk for harmful effects. The uncertainty in calculated critical load exceedances determined by these methods will allow the policy maker to decide an acceptable level of risk and set deposition targets accordingly.

Figure 7 shows a cumulative distribution function which was used to communicate the distribution of critical load exceedances for a single grid square (and ecosystem). Cumulative distribution functions have also been used in Europe to represent exceedance uncertainty spatially at the EMEP grid scale (Johansson and Janssen, 1994).

Figure 8 shows the results of a proposed classification scheme. The resultant analysis shows that most of coniferous 1km grid squares of Wales have uncertain exceedance. Other ecosystems would show different spatial patterns and the classification scheme could be adapted to increase the number of different classifications.

The third way of displaying the fuzziness of the exceedance assessment used was to calculate the probability of a given grid cell to exceed the critical load of acidity (Figure 9). The main advantage of this method is that it communicates both the *risk* of exceedance and the *area* at risk.

Finally the fuzzy nature of critical load exceedances may aid in the validation of critical loads. Measurements of pollution levels over the last ten years show a significant drop in acidic deposition. Steady-state calculations using deterministic critical loads and estimates of future pollution loads suggest major decreases in acidification damage by 2010. Falling emission levels will cut excess deposition over the critical loads substantially, although in some sensitive areas critical loads will still be exceeded. Ideally, areas with exceeded critical loads should correspond with areas in which acidification has occurred. Unfortunately, the steady-state nature of the concept precluded this simple approach. However this work has also shown that our estimates of excess deposition over critical loads may have large uncertainties. Thus the most likely outcome has to be estimated and also the likelihood of less severe or more severe outcome, i.e. the exceedance will vary between two extremes and we may not see the deterministic effect.

Different methods of presenting uncertain exceedance data have been brought together from the literature, applied to a case study and presented in this paper. These methods are not just applicable to the current application of acidity critical load exceedance but will also be applied to nutrient nitrogen and the heavy metal critical load methodologies. Indeed they can be applied to the setting of any sort of scientifically-based environmental quality standard. Feedback is required as to which of these methods would best suit the needs of the policy maker.

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Table 1 Acidity exceedance results for deterministic deposition data

Broad Habitat	Area Exceeded (km^2)	Accumulated Exceedance (keq/year)
Acid grassland	2 928 (93.1%)	248040
Calcareous grassland	0 (0 %)	0
Dwarf shrub heath	962 (89.3%)	49070
Bog	51 (91.6 %)	4800
Montane	18 (100 %)	2380
Coniferous woodland (managed)	464 (44.7 %)	22350
Deciduous woodland (managed)	255 (32.2 %)	9310
Unmanaged woods	79 (20.0 %)	1580
Freshwaters	43 (24.1 %)	2140
All habitats	4 800 (71.2 %)	339670

Table 2 (a) Area exceeded and percentage deviation from the deterministic values for area exceeded

Broad Habitat	Using 5%th ile deposition	Using 95th%ile deposition
Acid grassland	2 634 (-2%)	3 075(+5%)
Calcareous grassland	Remains at 0	Remains at 0
Dwarf shrub heath	472 (-10%)	1 046 (+9%)
Bog	46 (-1%)	52 (+3%)
Montane	17 (0%)	18 (0%)
Coniferous woodland (managed)	190 (-30%)	946 (+104%)
Deciduous woodland (managed)	77 (-48%)	543 (+102%)
Unmanaged woods	5 (-85%)	263 (+233%)
Freshwaters	23 (-26%)	72 (+67%)
All habitats	3 465 (-10%)	6 016 (+25%)

Table 2 (b) Percentage deviation from the median/nominal values for accumulated exceedance

Broad Habitat	Using 5th %ile deposition	Using 95th %ile deposition
Acid grassland	85 834 (-42%)	548 087(+121%)
Calcareous grassland	Remains at 0	Remains at 0
Dwarf shrub heath	8 849(-55%)	143 257(+192%)
Bog	1 960(-40%)	10 021(+109%)
Montane	922 (-28%)	4 903(+106%)
Coniferous woodland (managed)	4 318 (-60%)	97 815(+338%)
Deciduous woodland (managed)	1 674(-66%)	49 270(+429%)
Unmanaged woods	59 (-93%)	19 756(+1150%)
Freshwaters	380 (-60%)	4 968(+132%)
All habitats	104 000(-46%)	878 077(+159%)