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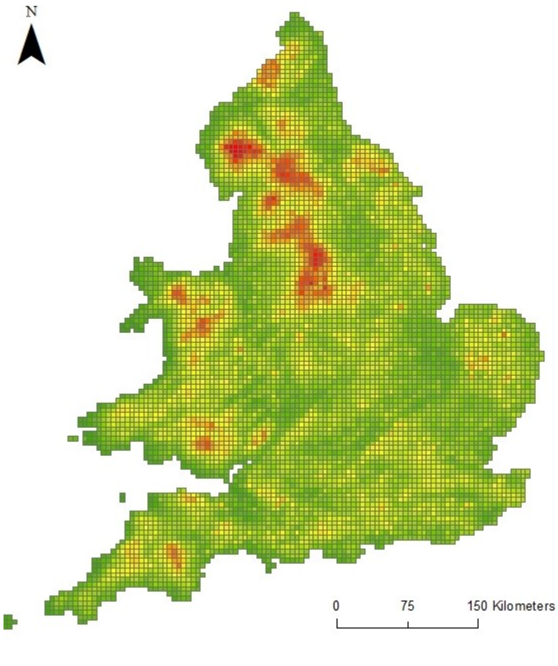
Atmospheric deposition at groundwater dependent wetlands:

Implications for effective catchment management and Water Framework Directive groundwater classification in England and Wales

Groundwater Programme

Internal Report OR/14/047



BRITISH GEOLOGICAL SURVEY

GROUNDWATER PROGRAMME
INTERNAL REPORT OR/14/047

Atmospheric deposition and groundwater dependent wetlands:

Implications for effective catchment management and future Water Framework Directive groundwater classification in England and Wales

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Front cover

CEBD nitrogen loading data on a 5x5Km grid from CEH.

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Foreword

This report is the product of an Environment Agency (EA) contract co-funded by the British Geological Survey (NERC) to review and collate information regarding atmospheric and terrestrial nutrient loading at groundwater dependent terrestrial ecosystems (GWDTEs) in both England and Wales (the inclusion of Welsh sites are covered by the co-funding from BGS and not from EA funding. Many GWDTEs are low nutrient systems therefore any increase in loading can have a detrimental effect upon the ecology. In order to better protect GWDTEs in England and Wales it has become increasingly important to understand the sources of nutrients so that effective regulation and management can be applied to return the GWDTEs into favourable condition. This report highlights many knowledge gaps and also provides the first comparison of two national assessments, Critical Load (assessment of atmospheric deposition) and Threshold Value (assessment of groundwater nitrate levels). It shows that nearly 90% of the GWDTEs in England and Wales exceed their Critical Load for atmospheric deposition. Implications for future Water Framework Directive classification cycles are highlighted. Suggestions are made for suitable GWDTEs to be included in a future research project. The project will aim to provide a methodology to define source attribution from both atmospheric and terrestrial nutrients, enabling environment managers to make effective decisions to project GWDTEs.

Acknowledgements

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Groundwater Dependent Terrestrial Ecosystems (GWDTEs) are wetlands that critically depend on groundwater flows and/or chemistries (Schutten et al. 2011) and include statutory (e.g. SSSI/SAC/NNR) and non statutory sites (e.g local nature reserves). There are a wide range of pressures that can lead to unfavourable condition at GWDTEs including: poor management, ineffective grazing regimes, historic and current drainage, and localised agricultural surface runoff. This report will focus upon pressures primarily from atmospheric deposition.

In order for the regulatory and conservation bodies to better protect these sites we need to know more about the relative sources, pathways and fate of atmospheric (and terrestrial) nutrients in GWDTEs. This knowledge base will allow for the design and implementation of successful Water Framework Directive (WFD) program of measures, and catchment management, aimed at reducing significant nutrient damage to GWDTEs, and other conservation/restoration initiatives.

Atmospheric nitrogen exists in oxidized and reduced forms, as wet or dry deposition. Oxidised nitrogen is sourced mainly from fossil fuels with reduced nitrogen (e.g. gaseous ammonia) more commonly associated with agriculture. Regulation of emissions has produced quantifiable reductions of atmospheric emissions (see RoTAP, 2012) including:

- **decrease in nitrogen oxides (NO_x) emissions of 58% between 1970 –2010**
- **decrease of ammonia (NH_3) emissions of 21% between 1990-2010**

Point sources such as factories are arguably easier to regulate than diffuse sources of atmospheric pollution, such as agriculture. These difficulties are reflected in data from RoTAP, (2012) showing that, although there has been a reduction in some emissions that there has been:

- **little change in concentrations of reduced nitrogen (as ammonia) deposition since 1990**
- **no change in total deposition of nitrogen (350-400kt-N per year) over the last 20 years**

Atmospheric deposition is mapped on a 5x5km grid scale for the UK using the CBED (concentration based estimated deposition) methodology; this allows every part of the UK to be assigned a figure for atmospheric deposition. The majority of SSSIs making up the GWDTEs in this study have been assigned a Critical Load value (in kg N ha^{-1} year^{-1}) to one or more habitat features, thus allowing the excess deposition above the critical load (i.e the exceedance) to be calculated.

Analysis shows that:

- **Critical loads can be applied to one or more feature habitats of 2355 of the 3320 GWDTEs in this study.**
- **Nitrogen deposition exceeds the critical loads for at least one habitat feature of 64% of the GWDTEs included within this study. However 965 sites in this analysis have no critical load, thus**

The Water Framework Directive classification requires a series of tests to be applied to each groundwater body in order to classify it in either ‘poor’ or ‘good’ status. One of these tests is the ‘Groundwater Dependent Terrestrial Ecosystem Test’ that uses the recently defined ‘Threshold Values’ for groundwater nitrate (UKTAG, 2012a) in conjunction with ecological evidence to classify each GWDTE. The most recent cycle of WFD classification suggests that:

- **6 groundwater bodies are classified as ‘Poor Status’ due to nutrient pressures. This number is likely to rise in the future as more data becomes available.**
- **65 groundwater bodies are considered probably at risk due to nutrient pressures on a GWDTE.**

The first comparison of Critical Loads and Threshold Values suggests the following:

England and Wales	
64%	**GWDTEs exceed their Critical Load (atmospheric) for one or more habitat features.** This figure is lower than expected as there are 865 sites with no critical load included within the dataset.
3 %	**GWDTEs exceed their Threshold Value (groundwater)**
3 %	**GWDTEs exceeded both the Critical Load and Threshold Value**

The analysis shows that nitrogen deposition exceeds the critical loads for at least one feature habitat for 90% of the GWDTEs (SSSIs) to which critical loads could be assigned, whilst a much smaller number exceed their groundwater Threshold Value. **However the Threshold Value results should be treated with caution** for two reasons;

- **it is likely that as more groundwater chemistry data is collected, that an increasing (although unknown) number of GWDTEs may exceed their threshold values, thus potentially failing the next WFD classification as many GWDTEs are also at risk from localised nutrient rich surface runoff and groundwater derived from agricultural processes.**
- **as more data and knowledge is gathered then it is possible that the existing nitrate threshold values (UKTAG, 2012a) may be refined and lowered and for specific sites this could result in a higher number of excedances.**

The 65 groundwater bodies currently at risk due to nutrient pressures at GWDTEs may be the most likely candidates to fail future classifications as more data is collected.

This analysis has implications for future WFD classification as it has become clear that there is still significant ambiguity as to the dominant sources and pathways (source attribution) for nutrients entering GWDTEs. This uncertainty has a direct effect on the regulatory bodies as it makes it more challenging to understand which actions to take to successfully eliminate or mitigate against these pressures.

- **There is a need for the collection of more water quality data at / or in WFD monitoring points considered to be hydrologically linked to GWDTEs. This would provide vital data for the future WFD classification of GWDTEs in England and Wales against existing threshold values.**

- **Nitrogen deposition exceeds the critical loads for one or more feature habitats of 64% of sites classed as GWDTE within this study, suggesting that effective catchment management must be considered together with the regulation of emissions from industry and agriculture to help GWDTEs achieve favourable status.**

Assessing the sources and pathways of nutrients at GWDTEs (source apportionment) is a critical part of the solution to better understanding, management and protection of GWDTEs. There are however numerous shortfalls in our understanding that limit our ability to assess the impact on the receptors, namely the vegetation at GWDTEs. Knowledge gaps (see Emmett et al. 2011) include;

- **poor understanding of time scale response of ecology to background N deposition.**
- **long term and historic monitoring data are rare, thus we do not know how many habitats have changed already.**

- **difficulty of separating the effects of other sources of nutrient input (e.g surface water runoff, and groundwater and surface water inputs) from atmospheric deposition- source apportionment.**

- **The combined nitrogen load from groundwater and atmospheric sources may exceed biological thresholds even where separately the critical load or GWDTE threshold are not exceeded.**

To address these issues it is proposed that a selection of GWDTEs in England and Wales will be selected for further study. The aim of this new study will be to undertake source attribution and loading for nutrients for both terrestrial and atmospheric sources, to directly inform the WFD program of measures, effective catchment management and site restoration/conservation programs.

Sites will be chosen based on the current pressures from atmospheric and terrestrial nitrate and habitat condition. Traditional and novel techniques will be used to attribute nutrients to their sources. It should be noted that by the term 'source apportionment' we are hoping to define the relative sources of pollution e.g. agriculture 60%, road traffic 40% and we are NOT trying to identify specific locations, e.g. Mr Smiths Farm. Existing Environment Agency nitrate loading tools will be used to model potential loading within groundwater catchments of GWDTEs. Only sites with pre-existing conceptual models and monitoring networks will be chosen as this will reduce cost and improve understanding. A multi agency expert working group will be formed to plan and oversee any future work.

1. Introduction

The Environment Agency, Natural England and Natural Resources Wales are responsible for the management of water and the environment in England and Wales. These responsibilities include the protection of Groundwater Dependent Terrestrial Ecosystems (GWDTEs). GWDTEs are wetlands that critically depend on groundwater flows and or chemistries (Schutten et al. 2011) and include statutory (e.g. SSSI/SAC/NNR) and non statutory sites (e.g local nature reserves). Examples of sites classified as GWDTEs include; fens, bogs, humid dunes and wet heath.

The regulatory bodies are charged with the successful implementation of both the Habitats Directive (92/43/EEC) and the Water Framework Directive (2000/60/EC). The Habitats Directive (HD) requires that member states should maintain or restore Annex 1 habitats to 'favourable conservation status', whilst the Water Framework Directive (WFD) requires groundwater to be in 'good chemical and quantitative status'.

As part of the WFD classification a series of tests are carried out on each 'groundwater body'. The results are used to assign either 'good' or 'poor' status to a groundwater body. One of these tests considers the impact of groundwater quality and availability on the condition of GWDTEs that are located within each groundwater body. In simple terms if a groundwater pressure such as over abstraction or elevated nutrients results in significant damage (see Whiteman et al. 2010) to a GWDTE then it is likely to fail both targets for the HD (remaining in 'unfavourable' condition) and the WFD (resulting in 'poor' status for the surrounding groundwater body). This report focuses on the GWDTE test that is part of the chemical classification process for the WFD (UKTAG, 2012b).

Two 'cycles' of groundwater characterisation have been undertaken in England and Wales (2008 & 2013). During each cycle GWDTEs in unfavourable status due to chemical (and quantitative) pressures have resulted in the failure of associated groundwater bodies. When a groundwater body fails the WFD classification the process requires an investigation to be undertaken, the identification of the source/s and reversal of the trends that lead to both unfavourable condition and poor groundwater status. These actions are known as WFD program of measures.

During WFD investigations at various wetlands (e.g. Environment Agency, 2011 and SWS, 2010a/b) it became clear that elevated nutrients were a key pressure resulting in unfavourable condition and poor status. To date WFD investigations have primarily been focused upon groundwater and surface water (i.e terrestrial) nutrient pathways.

GWDTEs can be ecologically and hydrologically complex, and when they are in unfavorable condition it can be easy to 'point the finger' at groundwater or surface waters as the pathway for nutrient enrichment. However there are other sources and pathways for nutrients, and atmospheric deposition is recognised as a serious threat to many UK habitats (e.g. Emmett et al. 2011). There is also ample evidence (e.g. Steven et al. 2011 and RoTAP, 2012) that exists to show that atmospheric nitrogen pollution is having adverse impacts on UK habitats, causing the loss of sensitive species and an overall decline in habitat quality (Emmett et al. 2011).

Being able to discriminate between atmospheric and terrestrial nutrient sources and pathways is vital for undertaking successful WFD classification and for implementing targeted and successful WFD program of measures to reduce sources and break pathways of nutrients to GWDTEs.

It is for these reasons that the Wetlands Task Team of the WFD UKTAG (UK Technical Advisory Group) highlighted the need to better understand the **fate and impact of aerial nutrient deposition on wetlands**. The conclusions of the RoTAP (2012) report also state '**further research to determine the ecological impacts of nitrogen on sensitive ecosystems** 'is required. At the time of writing a DEFRA project titled 'Identification of potential remedies for air pollution (nitrogen) impacts on statutory sites (RAPIDS) AQ0834' is underway and due for completion in late 2014 however the results of this work will not be available in time to include within this report.

The drivers for this work include:

> **effectiveness of WFD measures:** Understanding the mechanisms for nutrient inputs to wetlands will help to ensure WFD measures are, defensible, cost-effective and targeted on the correct sources of nitrogen.
>
> **identifying priority regulatory actions**: The provision of evidence will allow the identification of various sources of atmospheric deposition (e.g. power stations, poultry, other agriculture). When a source has successfully been identified it will become easier to implement actions aimed at reducing the sources of nutrients that contribute to unfavourable condition at many GWDTEs.

The key objectives of this project are to provide:

1. **critical review** of literature focusing on the fate, impact and influence of atmospheric nutrient deposition at GWDTEs and the result of these impacts on WFD groundwater status in England and Wales.

2. **desk based assessment of statutory sites, nutrient deposition** and WFD status across England and Wales.

3. **and to identify GWDTEs** that are suitable for source apportionment studies.

This report aims to provide the regulatory bodies in England and Wales with better information, allowing evidence based decisions to be made when implementing measures to address poor status at groundwater bodies and unfavorable condition at designated GWDTEs.

2. Nutrients and wetlands

The atmospheric deposition of nutrients, mainly nitrogen and its various chemical species, and its effects upon GWDTEs comprise the main focus of this report. The effects of elevated nitrogen deposition and a reduction in plant species richness is well documented (e.g. Stevens et al. 2010). The majority of GWDTEs considered within this report are low nutrient systems and exposure to prolonged or elevated levels of nutrients may cause significant ecological damage.

It is beneficial at this early stage to provide a brief description of the nitrogen cycle, also outlining sources of non-atmospheric nitrogen, the various species of nitrogen and the processes that facilitate the changes from one form of nitrogen to another. The description of the nitrogen cycle will be discussed in the following subchapters and will follow a **source-pathway-receptor** approach; the receptors in this example are GWDTEs.

The nitrogen cycle, simplified in Figure 1 illustrates the pathways and receptors for atmospheric nitrogen and inorganic and organic fertilizers in the environment. Future work requires an improved understanding and quantification of the N cycle, particularly relatively unstudied processes such as dry deposition, N fixation and decomposition/rnineralisation (Adams, 2003).

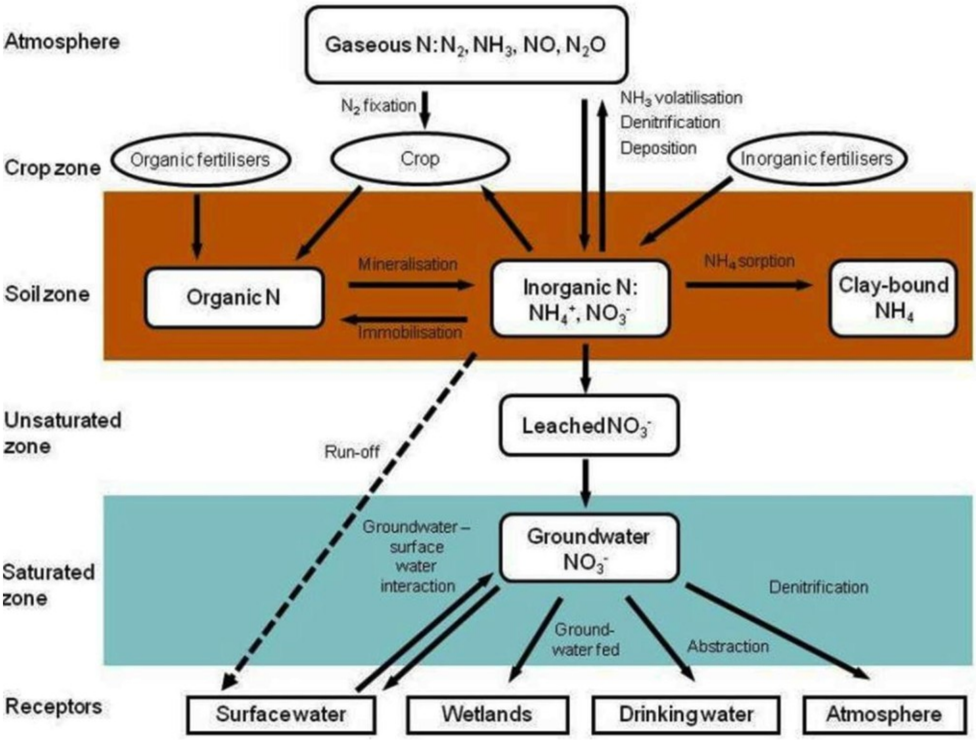

Figure 1 Simplified Nitrogen Cycle (BGS)

2.1 SOURCES OF ATMOSPHERIC NITROGEN

Atmospheric pollutants are diverse, and include nutrients as well as other pollutants such as sulphur, base cations, heavy metals and gases. This report focuses on atmospheric nutrients, primarily nitrogen and its species (both oxidized and reduced) that, in excess, can have a negative impact on GWDTEs. Atmospheric nitrogen can arise from a variety of natural and anthropogenic sources and can be deposited as both wet and dry deposition (EA, 2005). Nitrogen can originate from activities occurring both locally and over large areas. Natural sources can include forest soils, that can emit about 10-13% of N compounds that were originally deposited as NH_3 / $HN_4^+$and HNO_3/ NO_3-, back to the atmosphere as N oxides (Horvath et al. 2006). Lightning can also fix nitrogen from the atmosphere (Environment Agency, 2005) although this is not a major contributor to atmospheric deposition.

Dentrification is the process by which bacteria reduce nitrogen, resulting in the release of gaseous nitrogen (N_2) back into the atmosphere. Dentrification can occur within anaerobic areas of many wetlands which means that GWDTEs can themselves be a source of nitrogen. Drewer et al. (2010) show that peatlands can be both sources and sinks of nitrogen (and other green house gases) and calculate nitrogen budgets for two peatlands in Northern Europe. Anthropogenic addition of nitrate to wetlands may even act as a catalyist and enable increased levels of N_2O flux from wetlands (e.g. Liu and Greaver, 2009 and Moseman-Valtierra, 2011).

In addition to atmospherically derived nitrogen there are many anthropogenic and natural terrestrial sources of nitrogen. It is important to consider all sources of nitrogen that can potentially cause significant damage as this will improve future N budgets or source apportionment studies. Nitrates in groundwater are a widespread issue across the UK, with the application of fertilisers, sewage sludge and crop residues coupled with changes in landuse allowing both diffuse and point sources of nutrients to enter controlled waters (i.e groundwater and surface waters). Monitoring of nitrate levels in groundwater and surface water is established across England and Wales, with reporting undertaken for every groundwater and surface water body. Other anthropogenic sources of nitrogen in groundwater include: leaking sewers, application of sewage sludge to land, landfills and septic tanks (BGS, 1996). Terrestrial sources are often referred to as ‘diffuse pollution’ although ‘point sources’ such as non-mains waste water treatment and waste disposal can also contribute to the nitrate in controlled waters. In reality many dispersed point sources can appear to come from one single source of diffuse pollution (EA, 2005).

Oxidised and reduced nitrogen

Atmospheric nitrogen can be divided into two broad categories; oxidised and reduced (Table 1). When nitrogen (N) is oxidised it gains an oxygen molecule/s forming either nitric oxide (NO), nitrogen dioxide (NO_2), nitrous acid (HONO) or nitric acid (HNO_3) and if it is reduced it forms ammonia (NH_3). Oxidised and reduced nitrogen can be further divided on their sources; oxidised nitrogen tends to be sourced from anthropogenic combustion processes (e.g. power generation and traffic), whereas reduced nitrogen originates primarily from agricultural processes.

Oxidised Nitrogen	**Sources**
Nitrogen oxides(NO)	Combustion of fossil fuels from traffic and urban sources and industrial emissions. NO and NO_2 are collectively known as NO_x.
nitric oxide (NO)	
nitrogen dioxide (NO_2)	
nitrous acid (HONO)	
nitric acid (HNO_3)	also from nitrogen gas and water vapor during lightening strikes (not a major contributor to atmospheric nitrogen)
nitrate (NO_3-)	Wet deposition and via surface and groundwater
Reduced Nitrogen	**Sources**
Gaseous ammonia NH_3	Agriculture, livestock, poultry, manure management (cattle) also synthetic fertilizer application
Aerosol NH_4^+	Associated with SO_4^{2-} from emissions
Wet deposited NH_4^+	Agriculture: the effects of wet deposited NH_4^+ are thought to be less than that of dry deposited NH_3

Table 1 Sources of oxidised and reduced nitrogen, adapted from RoTAP (2012)

Nitrogen Oxides (NO_x)

NO and NO_2 are collectively known as NO_x and are formed when nitrogen (N) is oxidised forming nitrogen oxides (NO_x). The primary source for air emissions of nitrogen oxides (NO_x) are combustion sources e.g. road transport, public electricity and heat generation sector and industry (see RoTAP, 2012).

Ammonia (NH_3)

Ammonia (NH_3) emissions are primarily sourced from the agricultural sector, specifically manure management, degradation of urea from livestock (cattle) but also from synthetic fertiliser applications (RoTAP, 2012). The sources of ammonia (NH_3) can be both diffuse, sourced from large agricultural areas, and also from point sources such as pig and poultry farms, however many point sources can also produce diffuse pollution. The diffuse nature makes monitoring emissions for ammonia (NH_3) more uncertain than for the combustion generated nitrogen dioxides (NO_x). This also means that any modeled or spatial data will also be susceptible to the same uncertainties (RoTAP, 2012). This uncertainty will also apply to the 5 x 5 km grid square of atmospheric nitrogen deposition data used later on within this report (see Chapter 2.5).

2.2 PATHWAYS FOR ATMOSPHERIC NUTRIENTS

Once emitted to the atmosphere compounds are formed and transported often over long distances, subsequently being deposited in the form of pollutants such as particulate matter (sulphates, nitrates) and related gases (nitrogen dioxide, sulphur dioxide and nitric acid). Once in the atmosphere there are two processes by which deposition can occur, that is via 'WET' or 'DRY' deposition, both of which can be considered as direct pathways at GWDTEs. Wet deposition is the portion dissolved in cloud droplets and is deposited during rain or other forms of precipitation (EPA, 1999). Dry deposition includes both gas and particle transfer to surfaces during periods of no precipitation (EPA, 1999). Both the wet and dry deposition can be deposited directly upon GWDTEs.

Indirect pathways for atmospheric deposition involve: surface water, surface water runoff and groundwater to a GWDTE. The cumulative effect of atmospheric nutrient deposition across a groundwater body (or catchment of a GWDTE) must be considered for any successful source apportionment study and will be influenced by landuse, vegetation, soils, rainfall and topography.

Understanding the contribution of atmospheric loading and terrestrial loading on a catchment scale will be important for implementing effective and targeted management plans for both the WFD and HD. A general rule of thumb is that terrestrial loading at lowland habitats far exceeds loading from atmospheric sources.

2.3 RECEPTORS AND FACTORS AFFECTING ATMOSPHERIC NUTRIENT DEPOSITION AND LOSS

Atmospheric deposition does not discriminate and its effects are felt by a variety of receptors including: soils, freshwater and vegetation (see RoTAP, 2012) and also seawater where nutrients can contribute to algal blooms. Responses and changes to atmospheric deposition occur in soils, freshwater and vegetation and affect a wide range of ecosystems (RoTAP, 2012). Atmospheric deposition is an important source of N in semi-natural upland ecosystems (Helliwell et al. 2007) as many upland systems maybe exposed to less terrestrial nitrogen sources due to their topographical setting and surrounding low intensity land use. In the context of this report vegetation at GWDTEs must be considered as the principal receptor because most GWDTE are defined in terms of vegetation characteristics and it is change within the vegetation that is used to determine if a GWDTE is in unfavourable condition.

Vegetation

There is strong evidence that the effect of nitrogen deposition on vegetation in general (and not just GWDTEs) has already been reflected by a significant reduction in total plant species, diversity and frequency of sensitive plant species since the 1980s (RoTAP, 2012). The effects of atmospheric N deposition on species diversity is not straight forward and for any given habitat it will depend on abiotic conditions including: buffering capacity, soil nutrient status and soil factors that influence the nitrification potential and nitrogen immobilisation rates (Bobbink et al. 1998). Maskell et al. (2010) found a strong negative correlation between atmospheric nitrogen deposition and plant species richness in selected habitats (heathland acid, calcareous and mesotrophic grassland) in the UK. Maskell et al. (2010) also highlights the complexity and interactions of land management and grazing and their influence on the susceptibility of sites to nitrogen deposition. Nitrogen deposition has also been shown to have a cumulative impact (e.g Dupre et al. 2010). The national 5x5 km deposition maps (see Chapter 2.5) are based on annual mean deposition rates; the difficulty of quantifying the effect of cumulative deposition should be considered especially during any future source apportionment study. Furthermore Stevens et al. (2011) highlight the ability of certain species to be impacted even at low levels of nitrogen deposition – even below that of the critical loads (for explanation of critical loads see Chapter 4).

Changes in vegetation can also result from the failure to implicate suitable grazing regimes, abandonment of sites (i.e no management) or historic management decisions such as the stabilization of many dune systems across coastal areas in the UK. It is important to consider how the effects on vegetation of land management changes and vegetation management can be distinguished from the effects of atmospheric (and terrestrial) impacts during any source apportionment study.

Vegetation is the primary receptor for atmospheric deposition at many GWDTEs. CSM or common standards monitoring (see JNCC, 2004) and repeat surveying of vegetation is used to identify indicator species that are related to nutrient enrichment. The first six year report on common standards monitoring Williams (2006) states: It is often very difficult to determine the effects of air pollution natuural or semi natural habitats, given the complex interactions between pollution impacts, management and abiotic influences. As a result, the impacts of air pollution, and the identification of air pollution as an adverse activity affecting condition, are considered to be substantially under-reported in this assessment.

There are however some concerns regarding this approach and these are raised by Emmett et al. (2011) and also summarized in Chapter 12 within this report. Different habitats are assigned nitrogen critical loads (ie, thresholds for the impacts from atmospheric deposition; these are discussed in more detail in Chapter 4) and recent data analysis (Stevens et al. 2011 and Emmett et al. 2011) show that for many habitats across large areas of the UK, nitrogen deposition exceeds the critical loads.

Soils

Topsoil nitrogen concentration has decreased in many habitats despite continued total atmospheric nitrogen deposition remaining the same over the last 20 years (RoTAP, 2012). The reasons for this are not known but could be associated with changes in the C:N ratios such that the nitrogen signal is diluted by increased C fixation by plants or that microbioal activity has been effected by N deposition, thus increasing the availability of N to plants, RoTAP (2012). Nitrogen (N) is however immobile in soil organic matter, relatively little is leached to freshwaters (RoTAP, 2012) and it is therefore important to consider cumulative nitrogen (N) deposition rather than present day deposition (Emmett et al. 2011). The importance of abiotic conditions including soil nutrient status and buffering capacity all affect the ability for NO_3- / NH_4 nitrification and mobilisation (Bobbink et al. 1998) and thus the impact it can have on any receiving ecosystem.

A study into four UK upland catchments (Helliwell et al. 2007) describes how nitrogen concentrations in acid sensitive upland soils were greater in areas dominated by mineral soils with a small C-pool rather than peaty soils (large C –pool). Helliwell et al. (2007) conclude that if nitrogen deposition remains at current levels then it is possible that upland catchments with small C – pools will be more susceptible to NO_3- leaching, thus having a direct impact on habitats and freshwater systems that receive water from these upland catchments. Helliwell et al. (2007) describe how the geomorphology (slope, altitude and bare rock) of upland catchments may provide a control for winter NO_3- leaching and how in the summer significant relationships between the C pool and surface water NO_3- were observed. The implication for this is that any GWDTEs that receive an element of surface water flow from an upland catchment may also be indirectly impacted by the ability of the soils and other geomorphological characteristics to limit (or enhance) leaching of NO_3- during the year. Source apportionment studies or models to understand atmospheric nitrogen deposition across groundwater bodies would need to consider soil types, slope, altitude and areas of bare rock within the analysis.

Seasonal variation and climate change

The natural variability of rainfall (intensity and amount) varies seasonally across England and Wales, with winter periods traditionally being wetter than summer periods. This natural variability of rainfall has a direct influence on wet atmospheric deposition, and this is factored into the Concentration Based Estimated Deposition (CBED: RoTAP, 2012) data for England and Wales (see chapter 2.5). During winter biological uptake and transformation of nitrogen is greatly reduced (Helliwell et al. 2007) and this also generally corresponds with periods of greater rainfall and wet deposition.

Nitrogen loss from wetlands can also vary throughout the year as seasonal patterns of organic carbon (important for dentrifying bacteria) loss changes depending upon plant types and their ability to create varying amounts of litter (Weisner et al. 1994).

The potential effects of climate change on air pollution impacts on soils and vegetation are potentially very wide-ranging and are discussed in more detail in the RoTAP (2012) report. The RoTAP report summarises the three main potential impacts of climate change on atmospheric deposition, they include;

(i) changes in the tolerances of plant species to soil acidification and N enrichment under different climate conditions;
(ii) increased frequency of climatic stresses to which air pollution increases sensitivity (e.g. drought); and
(iii) increased uptake, weathering and leaching of N and base cations and increased base cation weathering due to climate-induced changes in plant growth and hydrological conditions

2.4 ATTENUATION OF NITROGEN IN WETLANDS

Attenuation of nitrogen in wetlands is a complex subject and although it must be mentioned it is beyond the scope of this project to deal with it in detail. The following is a very short description of some key issues related to the attenuation of nitrogen in wetlands, and a detailed review of the literature is needed to expand further upon this subject.

Nitrogen can be both retained, attenuated and lost (i.e. cycled) within many GWDTEs and the key processes associated with this are; nitrification, denitrification and uptake by plants. Dentrification is the primary mechanism for nitrogen retention (Saunders and Kalff, 2001) and occurs in anoxic environments when bacteria use the oxygen in nitrate for respiration and release N gas back to the atmosphere (Woods Hole Group, 2007). Denitirification also depends upon the release of organic carbon from plant litter and living macrophytes, which is used directly by denitirfying bacteria within wetlands and also indirectly by stimulating a lower redox potential (Weisner et al. 1994).

In upland systems nitrogen is generally tightly cycled and retained, with minimal release to surface water or groundwater. However nitrogen saturation can occur in some systems if deposition exceeds the retention capacity of soils and biota in the system (Helliwell et al. 2007). The ability of wetlands to retain nitrogen has been highlighted by several studies: Chapman and Edwards, (1999) and Davies et al. (2005) suggest that the dominance of NO_3^- in inorganic N leaching in semi natural systems is due to the retention of NH_4^+ via uptake, adsorption or nitrification within the ecosystems. Jansson et al. (1998) describe the ability of wetlands in the Baltic sea drainage basin to retain 5-13% of atmospheric and terrestrial nitrogen, preventing eutrophication in the Balitic sea; however the potential of damage to the actual wetlands is not discussed in detail.

2.5 MODELLING OF ATMOSPHERIC DEPOSITION IN THE UK

The deposition data used within this report, and also for the APIS (Air Pollution Information System) website (www.apis.ac.uk) is calculated on a 5 x 5 km grid using the CBED (Concentration Based Estimated Deposition) methodology. Maps are produced of wet and dry deposition of sulphur, oxidised and reduced nitrogen, and base cations using measurements of air concentrations of gases and aerosols as well as concentrations in precipitation from the UK Eutrophying and Acidifying Pollutants (UKEAP) network (Hall et al. 2014 [in press]). Site based measurements are interpolated to generate maps of concentrations for the UK. The ion concentrations in precipitation are combined with UK Met Office annual precipitation data to generate wet deposition. Gas and particulate concentration maps are combined with spatially distributed estimates of vegetation-specific deposition velocities (Smith et al. 2000) to generate dry deposition. Examples of these maps are presented in Figure 2.

More detail on CBED can be found in RoTAP (2012); some of the key points are listed below:

- Dry deposition of oxidized nitrogen is generated using data calculated from and interpolated between 30 sites

- The use of vegetation-specific deposition velocities enables different deposition values to be derived for deposition to different land cover types; for critical load exceedances, values for moorland are applied to all non-woodland habitats, and deposition values for woodland are applied to all woodland habitats.

- Wet deposition mapping requires the use of an orographic enhancement factor which accounts for the natural variability in annual rainfall conditions which directly influences wet deposition.

- Deposition data used for calculating critical load exceedances are 3-year annual averages of the sum of wet plus dry deposition to moorland and woodland.

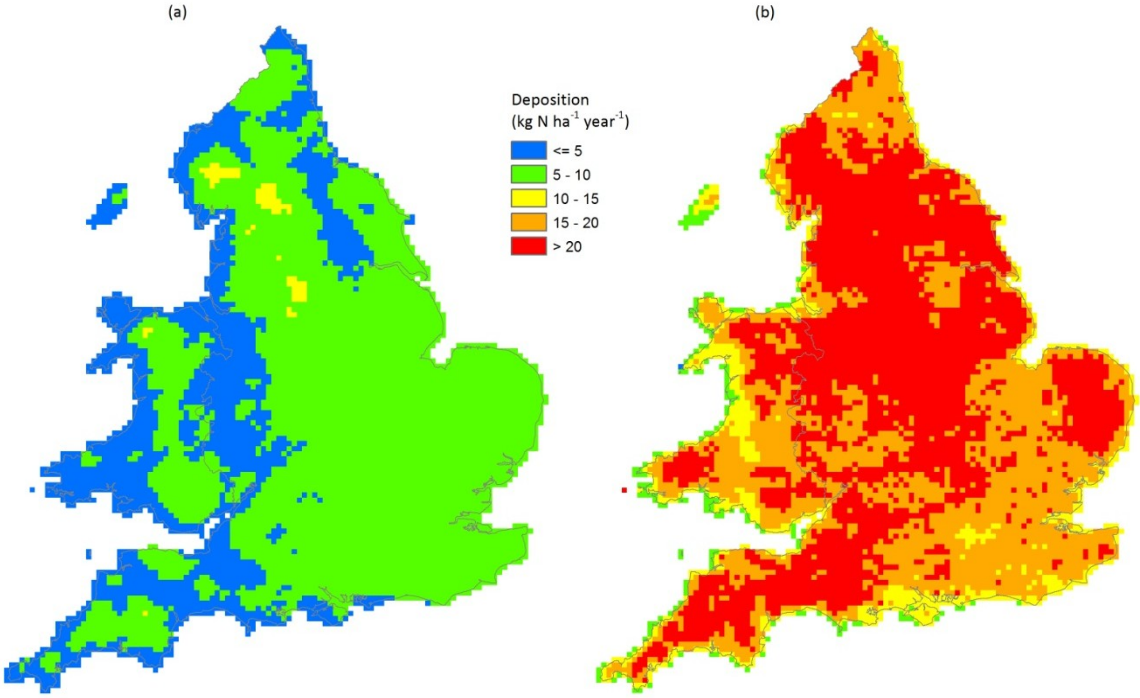

Figure 2 CBED 5x5 km nitrogen deposition to moorland for 2010-12: (a) oxidized nitrogen; (b) total (oxidized + reduced) nitrogen. *Contains OS data © Crown Copyright and database right [2015]*

There are several different models that can be used for air pollution modeling for both long (>50km) and short range (<20km) predictions, the main output being to provide an estimate of a concentration of deposition of a pollutant. The APIS (Air Pollution Information System) website (www.apis.ac.uk) is one of the main portals to this information and further details of modeled concentration and deposition values in the UK can be found in RoTAP, 2012 (Chapter 4) and at pollutantdeposition.defra.gov.uk.

3. European Directives

3.1 THE HABITATS DIRECTIVE AND CONSERVATION STATUS

‘Council Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora’ more commonly known as the ‘Habitats Directive’ was adopted into UK law in 1992. The Habitats Directive contains a list of habitats in Annex 1 (e.g. ‘Humid Dune Slacks 2190) and then a list of species in Annex II (e.g. *Liparis loeselii* the Fen orchid). Some of the Annex 1 habitats and Annex II species may also be classed as ‘priority habitats/species’.

The main aim of the Habitats Directive is to promote the maintenance of biodiversity by requiring Member States to take measures to maintain or restore natural habitats and wild species listed on the Annexes to the Directive at a favorable conservation status, introducing robust protection for those habitats and species of European importance (http://jncc.defra.gov.uk/page-1374).

As part of the Habitats Directive each member state is required to report every six years on the conservation status of the listed habitats and species in the directive. This six yearly reporting is often referred to as ‘Article 17’ reporting and at the time of writing three rounds of this reporting have been undertaken. Each Annex 1 habitat or Annex II species is given a conservation status for example ‘unfavourable’ or ‘favourable’ based on the various individual and combined pressures that can contribute towards a GWDTEs condition assessment. Common Standards Monitoring is the standardized way to provide site specific condition assessment for SSSI and SACs (see JNCC, 2004) and depends upon a variety of condition components including presence and/or abundance of negative or positive indicator species.

Atmospheric nutrient deposition (although just one of many pressures facing GWDTEs) can have a wide ranging impact on the conservation status of designated sites (Emmett et al. 2011) including;

- change in habitat (and species composition) due to change in habitat structure and function
- loss or reduction of habitat size due to loss of species or actual habitat and potential reclassification as a different habitat (e.g heathland to acid grassland).
- and the cumulative deposition of nitrogen (N) building up within the soil

3.2 THE WATER FRAMEWORK DIRECTIVE AND GROUNDWATER STATUS

As part of the WFD classification the chemical and quantitative status of each groundwater body must be assessed by applying a series of tests (UKTAG, 2012b). There are 305 individual groundwater bodies in England and Wales. The tests applied to each groundwater body include: ‘saline or other intrusions, surface water, **groundwater dependent terrestrial ecosystems**, drinking water protected areas, general quality and a water balance test’. The results are used to assign either ‘Good’ or ‘Poor’ status to each groundwater body.

The Groundwater Dependent Terrestrial Ecosystems test considers the impact of groundwater quantity (UKTAG, 2012a) and quality (UKTAG, 2012b) on the condition of the wetland. When a groundwater pressure such as over abstraction or elevated nutrients results in significant damage (Whiteman et al. 2010) the result is the failure of the WFD test, resulting in ‘Poor’ status for the surrounding groundwater body.

Two ‘cycles’ of groundwater classification have been undertaken in England and Wales (2008 & 2013). During each cycle the GWDTE test was applied to each groundwater body. During the first assessment the test was basic and this was due to a lack of site specific information, namely qualitative and quantitative hydroglogical data (water levels and water quality) and also a poor understanding of baseline water levels and water quality from comparable habitats.

The 2nd Cycle benefited from several years of investigation (e.g. Environment Agency, 2011 and SWS, 2010a/b), publication of several 'Ecohydrological Guidelines' (e.g. Environment Agency, 2010). The derivation of '**Threshold Values'** for nitrate for a range of key wetland types that broadly conform to Annex I habitats (UKTAG, 2012a) also allowed more detailed assessment during the 2nd Cycle. The threshold values are empirically derived and are based on wetland condition (i.e favorable or unfavorable) and levels of nitrate within a WFD groundwater monitoring point hydrologically linked to a GWDTE. Threshold Vales were used to identify where rising trends of nitrate in groundwater bodies are likely to cause pressures in hydrogeologically connected GWDTEs. The threshold value methodology does acknowledge that atmospheric deposition is a source of nitrogen to GWDTE however no attempt is made to proportion the loading from terrestrial or atmospheric sources within the methodology.

The need to understand the contribution of atmospheric deposition v input of nutrients from the terrestrial environment is important to avoid Poor Status being assigned to a groundwater body, especially if atmospheric deposition is the main cause for unfavorable GWDTE condition. The need to 'untangle' and quantify the sources of terrestrial v atmospherically derived nutrients (source apportionment) is essential for successful application of the WFD. Understanding the sources of nutrient pressure is also vital when it comes to designing and implementing programs of measures (such as land management changes) to improve the status of GWDTE and ultimately the associated groundwater bodies. If we have not quantified the main source of the nutrients (e.g. atmospheric or terrestrial) then it is impossible to target actions to break the pathways to the GWDTE. The knowledge gap was recognised by the UKTAG wetlands task team and is the driving force behind this project.

Table 2 summarizes the results of the 2nd cycle WFD classification GWDTE test. Both chemical and quantitative data are shown for comparison, however it should be noted that quantitative failures are not linked to atmospheric deposition.

Chemical pressures at GWDTE resulted in the Poor Status classification of 6 groundwater bodies (2 in England and 4 in Wales). The remaining 303 groundwater bodies in England and Wales were classified as being in Good Chemical Status for the GWDTE test although 198 of these were classified as Good Status but 'Probably at Risk'.

In comparison quantitative pressures resulted in the failure of 4 groundwater bodies, all in England reflecting the greater abstraction of groundwater in England than in many parts of Wales. No further discussion on the quantitative assessment is necessary for this report and the list of poor quantitative status groundwater bodies is supplied for information only.

			Chemical Assessment		
	ID	Groundwater Body	Status	Confidence	Risk
England	GB41202G102100	South Cumbria Lower Palaeozoic and Carboniferous Aquifers	Poor		At Risk
	GB41202G991700	Weaver and Dane Quaternary Sand and Gravel Aquifers	Poor	Low	Probably At Risk
Wales	GB41001G201300	Swansea Southern Carboniferous Limestone	Poor	High	At Risk
	GB41001G204200	Ynys Mon Central Carboniferous Limestone	Poor	High	At Risk
	GB41002G200400	Cleddau and Pembrokeshire	Poor	High	Probably At Risk
	GB41002G204600	Llyn & Eryri	Poor	High	At Risk

			Quantitative Assessment		
	ID	Groundwater Body	Status	Confidence	Risk
England	GB40501G400500	Cam and Ely Ouse Chalk	Poor	Low	At Risk
	GB40601G501300	Basingstoke Chalk	Poor	Low	At Risk
	GB40601G602000	Regate Lower greensand	Poor	Low	At Risk
	GB40901G300800	Worcestershire Middle Severn	Poor	High	At Risk

Table 2 WFD Chemical and Quantitative Classification (2nd Cycle, 2013). Groundwater bodies that have been assigned Poor Status due to pressures on a GWDTE.

Groundwater Bodies (GWBs) in Good Chemical Status can be further broken down into:

- 2 GWB's in Good Status, High Confidence and At Risk
- **105 GWB in Good Status, High Confidence and Probably At Risk (of which 65 are considered probably at risk due to pressures on a GWDTE).**
- 51 GWB in Good Status, High Confidence and Not At Risk
- 40 GWB in Good Status, High Confidence and Probably Not At Risk
- 4 GWB were considered Good Status, Low Confidence and At Risk
- 5 GWB were considered Good Status, Low Confidence and Not At Risk
- 92 GWB were considered Good Status, Low Confidence and Probably Not At Risk

A total of 6 GWB were classified at 'Poor Status' as a result of the GWDTE test. It is perhaps more important to consider the number of groundwater bodies that are 'Probably at Risk'. In England and Wales a total of 65 GWB were classified as Good Status but Probably at Risk, due to chemical pressures in the GWDTE test, their locations are illustrated in Figure 3. It is possible that as more data is collected that some of the Probably at Risk groundwater bodies may indeed be re classified as At Risk in future classification cycles.

Investigations carried out by the Environment Agency and Natural Resources Wales (Environment Agency, 2011 and SWS, 2010a/b) highlighted that nutrient pressures were a key source of unfavourable condition at many GWDTEs, resulting in poor status for associated groundwater bodies.

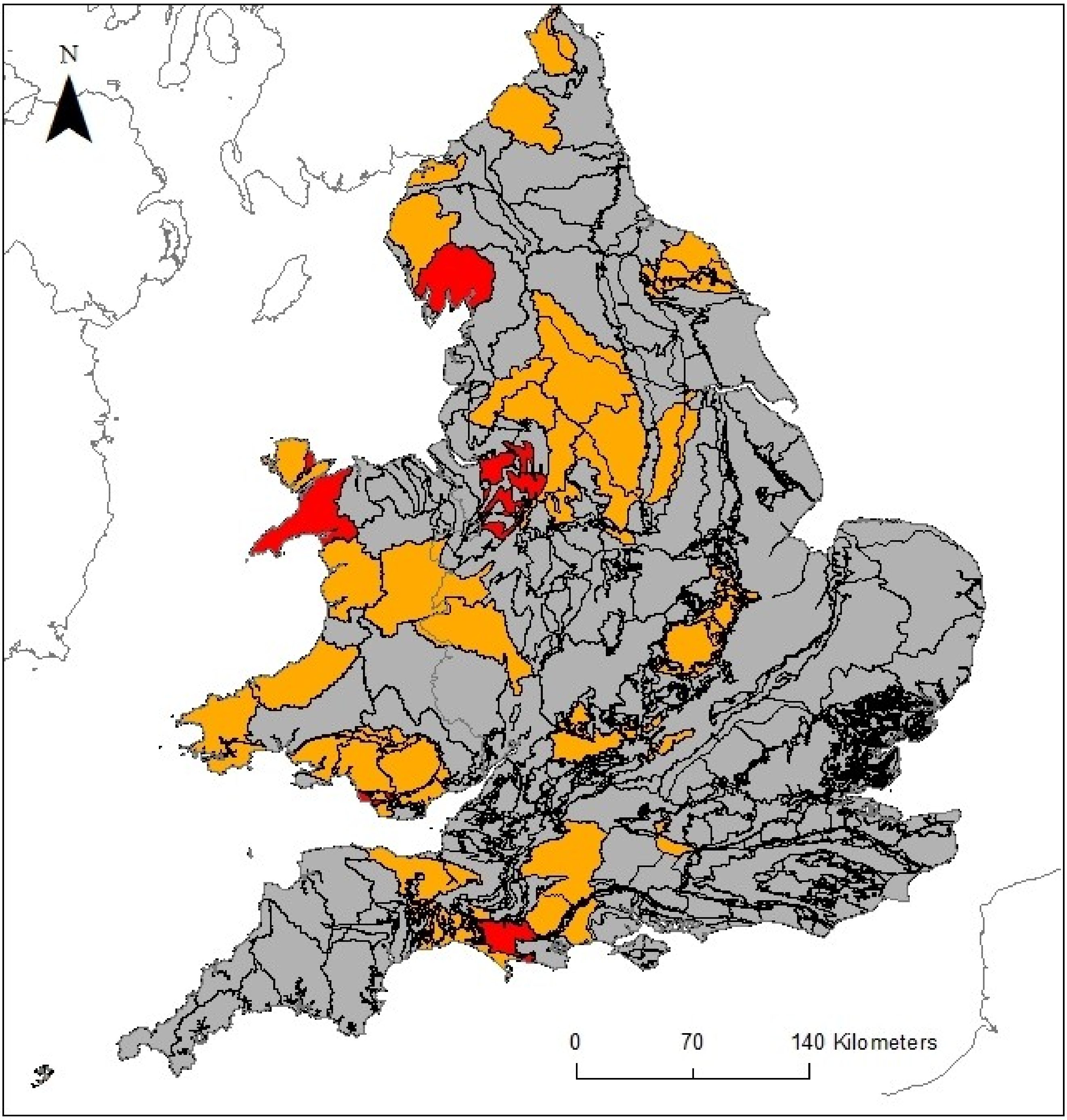

Figure 3 WFD groundwater bodies At Risk (red) and Probably At Risk (orange) due to pressures at designated groundwater dependent terrestrial ecosystems in England and Wales (2nd Cycle).
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4. Critical Loads

Critical loads are a quantitative estimate of exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge (Nilsson & Grennfelt, 1988). In the UK critical loads are applied to broad habitats sensitive to acidification and/or eutrophication; this report considers only empirical critical loads for eutrophication (nutrient nitrogen) from atmospheric nitrogen.

Critical loads for nitrogen are published as a range (Bobbink & Hettelingh, 2011) to encompass the variability in response of habitats to nitrogen. In the UK, a single value within these ranges has been chosen for the calculation of critical load exceedances; this "mapping value" is based on UK evidence of nitrogen impacts (Hall et al. 2011; 2014 in press). Nitrogen Critical loads are reviewed and updated under the Convention on Long Range Transboundary Air Pollution (CLRTAP), the last review being in 2010 (Bobbink & Hettelingh, 2011). Critical loads have been derived for seven ecosystem types: mire, bog and fen; grasslands; heathland, scrub and tundra; woodland and forest; inland surface waters; coastal; marine. In the UK critical loads have been mapped for N habitat types: acid grassland, calcareous grassland, dwarf shrub heath, montane, bog, managed and unmanaged woodlands, dune grassland and saltmarsh (Table 3). The critical loads are applied to each 1x1 km square of national-scale habitat distribution maps (Hall et al. 2011;2014 in press) and then compared with national 5x5 km resolution atmospheric N deposition maps. Where the deposition is greater than the critical load (ie, the critical load is "exceeded") the habitat is considered to be at risk from adverse impacts from excess nitrogen deposition (Figure 4a).

The latest analysis (based on CBED annual mean deposition for 2010-12) shows that:

- **N deposition exceeds the critical loads across 65% of the total area of UK habitats sensitive to eutrophication**

The above national-scale analysis is based on the areas of all nitrogen sensitive broad habitats mapped in the UK. The current study in relation to GWDTEs considers all designated habitat features (ie, not just "wetland" habitats) found within SSSIs in England and Wales that are sensitive to nitrogen, and for which nitrogen critical loads are available. Critical loads are not available for some habitat feature types due to a lack of sufficient published data and evidence of nitrogen impacts. In addition, some SSSIs may contain habitat features that are not sensitive to nitrogen deposition. Consequently, in this study, critical loads were applied to 2355 of the 3320 sites, with no critical loads available for 965 sites.

The critical load values applied to the sensitive habitat features of SSSIs may differ from those applied to the broad habitats mapped nationally (Table 3). The Statutory Nature Conservation Bodies have set "recommended" values from within the published ranges, for use in Article 17 reporting for the Habitats Directive, and these are the critical load values that have been used in this study. In many cases these "recommended" values are the same as the "mapping values", but for some habitats they may be the minima of the published range; in particular for habitats where there is less UK evidence available, or for habitat types not mapped nationally. Critical loads have been applied (where available) to each nitrogen-sensitive feature habitat within each site; these critical loads may vary from one habitat to another (Table 3). This also means that critical load exceedance may vary from one habitat to another. For national scale work the exceedance metric "Average Accumulated Exceedance" is frequently mapped (see Figure 5b); in this study a precautionary approach has been taken, by using the maximum exceedance (rather than AAE) per site (SSSI). It should also be noted that historically due to a lack of digital data on the spatial location of feature habitats within each site, it is assumed in this data analysis that all feature habitats can occur anywhere and everywhere within each site.

As with many other target values not all sites may follow the rules and in some cases impacts (on designated sites) can be seen below the critical loading value for nitrogen (Stevens et al. 2011).

Habitat type	EUNIS code[1]	Critical load range (kg N ha^{-1} year^{-1})	UK Mapping Value[2] (kg N ha^{-1} year^{-1})	Recommended Value[3] (kg N ha^{-1} year^{-1})
Marine habitats				
Mid-upper saltmarshes	A2.53	20-30 (#)	25	N/A
Pioneer & low saltmarshes	A2.54/55	20-30 (#)	25	N/A
Coastal habitats				
Shifting coastal dunes	B1.3	10-20 (#)	not mapped	10
Coastal stable dune grasslands	B1.4[a]	8-15 #	9 acid dunes 12 non-acid dunes	8
Coastal dune heaths	B1.5	10-20 (#)	not mapped	10
Moist to wet dune slacks	B1.8[b]	10-20 (#)	not mapped	10
Inland surface water habitats				
Softwater lakes (permanent oligotrophic)	C1.1[c]	3-10 ##	not mapped	3
Permanent dystrophic lakes, ponds, pools	C1.4[d]	3-10 (#)	not mapped	3
Mire, bog & fen habitats				
Raised & blanket bogs	D1[e]	5-10 ##	8,9,10 (rainfall dependent)	5
Valley mires, poor fens & transition mires	D2[f]	10-15 #	not mapped	10
Rich fens	D4.1[g]	15-30 (#)	not mapped	15
Montane rich fens	D4.2[g]	15.25 (#)	not mapped	15
Grassland & tall forb habitats				
Semi-dry calcareous grassland	E1.26	15-25 ##	15	15
Dry acid & neutral closed grassland	E1.7[b]	10-15 ##	10	10
Inland dune pioneer grassland	E1.94[b]	8-15 (#)	not mapped	8
Inland dune siliceous grassland	E1.95[b]	8-15 (#)	not mapped	8
Low & medium altitude hay meadows	E2.2	20-30 (#)	not mapped	20
Mountain hay meadows	E2.3	10-20 (#)	not mapped	10
Molinia caerulea meadows	E3.51	15-25 (#)	not mapped	15
Juncus meadows & Nardus stricta swards	E3.52	10-20 #	15	10
Moss & lichen dominated mountain summits	E4.2	5-10 #	7	7
Alpine & subalpine acid grassland	E4.3	5-10 #	not mapped	5
Alpine & subalpine calcareous grassland	E4.4	5-10 #	not mapped	5
Heathland, scrub & tundra habitats				
Arctic, alpine & subalpine scrub	F2	5-15 #	not mapped	5
Calluna dominated upland wet heaths	F4.11[e,h]	10-20 #	10	10
Erica tetralix dominated lowland wet heaths	F4.11[e,h]	10-20 (#)	10	10
Dry heaths	F4.2[e,h]	10-20 ##	10	10
Forest habitats				
Broadleaved woodland	G1	10-20 ##	12	10
Beech woodland	G1.6	10-20 (#)	15	15
Acidophilous oak dominated woodland	G1.8	10-15 (#)	10	10
Coniferous woodland	G3	5-15 ##	12	10
Scots Pine woodland	G3.4	5-15 #	12	12

Table 3. Critical loads of nutrient nitrogen showing published ranges (Bobbink & Hettlingh, 2011) and values applied in the UK (Hall et al. 2011)

Footnotes:

[1] Habitat class of the European Nature Information System (EUNIS); these are the habitat classes for which the nutrient nitrogen critical load ranges have been set within Europe (Bobbink & Hettelingh, 2011).

[2] The single value from within the range used for national-scale critical loads mapping for UK broad habitats, based on UK evidence of nitrogen impacts (Hall, 2011).

[3] The single value from within the range set by UK SNCBs for site-specific applications to habitat features of designated sites and used for Article 17 Reporting under the Habitats Directive.

Reliability scores assigned to critical load ranges (Bobbink & Hettelingh, 2011):

reliable: when a number of published papers of various studies showed comparable results.
quite reliable: when the results of some studies were comparable.
(#) expert judgement: when no empirical data were available for the ecosystem; critical load based upon expert judgement and knowledge of ecosystems which were likely to be comparable with this ecosystem.
Table 3 Footnotes continued (Bobbink & Hettelingh, 2011):
[a] For acidic dunes, the 8-10 kg N ha^{-1} $year^{-1}$ range should be applied; for calcareous dunes the range 10-15 kg N ha^{-1} $year^{-1}$ should be applied.
[b] Apply the lower end of the range to habitats with low base availability, and the higher end to those with high base availability.
[c] This critical load should only be applied to oligotrophic waters with low alkalinity with no significant agricultural or other human inputs.
[d] This critical load should only be applied to waters with low alkalinity with no significant agricultural or other direct human inputs.
[e] Apply the high end of the range to areas with high levels of precipitation and the low end of the range to those with low precipitation. Apply the low end of the range to systems with a low water table and the high end of the range to those with a high water table.
[f] For EUNIS category D2.1 (valley mires) use the lower end of the range.
[g] For high latitude systems apply the lower end of the range
[h] Apply the high end of the range to areas where sod cutting has been practiced; apply the lower end of the range to areas with low-intensity management.

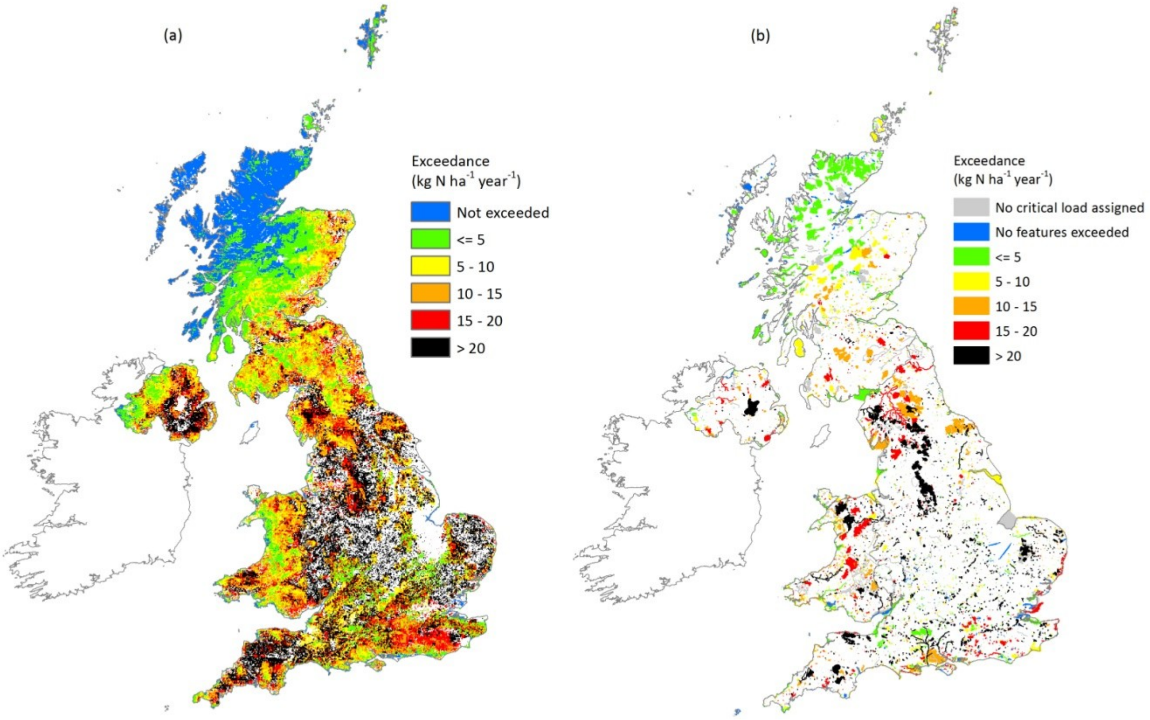


Figure 4 Examples of national-scale critical load exceedance maps generated under Defra contract AQ0826: (a) Average Accumulated Exceedance (AAE) of nitrogen critical loads for sensitive UK habitats by CBED total nitrogen deposition for 2010-12; (b) Maximum AAE of nitrogen critical loads per SSSI by CBED total nitrogen deposition (area-weighted value per SSSI) for 2010-12. AAE is an exceedance metric that averages exceedance over the entire sensitive habitat area; it is calculated as:

AAE= (∑exceedance*exceeded area) ÷ total sensitive habitat area. *Contains OS data © Crown Copyright and database right [2015]*

5. Monitoring networks in England and Wales

There are several monitoring networks established across the UK designed to collect data to understand baseline atmospheric deposition. Only maps for England and Wales are presented as figures however all of the networks within this chapter have sites in Scotland and Northern Ireland. A short description of each network along with a map showing the location of the monitoring points are provided in the following chapter. A large amount of the data from these monitoring networks is available online via the DEFRA website, and for each a web address is supplied. This section will only provide an overview of the national monitoring networks (including the Large Plant Combustion Directive sites) and a list of individual sites is provided in Chapter 10. **A spatial GIS search shows that > 50% of the atmospheric monitoring sites are within 10km of a designated GWDTE.**

5.1 UK EUTROPHYING AND ACIDIFYING ATMOSPHERIC POLLUTANTS (UKEAP)

UKEAP consists of four monitoring networks measuring atmospheric acidifying and eutrophying species in the rural environment, and the operation of the two UK EMEP supersites one in Scotland (Auchencorth Moss) and the other in England (Harwell, Oxfordshire). The network is run jointly by the Centre for Ecology and Hydrology (CEH) and AEA Technology and aims to allow:

- The evaluation of policy measures to reduce concentration and deposition
- Risks to ecosystems and exceedences of critical loads to be assessed

Annual reports for the network are publically available e.g. Connolly et al. (2011) and a short description of the networks that make up the UKEAP are provided below.

5.2 NATIONAL AMMONIA MONITORING NETWORK (NAMN)

Gaseous ammonia (NH_3) has been measured monthly at 85 sites across the UK since 1996 (Figure 5). The monitoring provides a baseline in the reduced nitrogen species (NH_3 + NH_4^+), which is necessary for examining responses to changes in the agricultural sector and to verify compliance with targets set by international agreements. Samples are collected using the CEH DELTA (Denuder for long Term Atmospheric sampling) system. The data for each of the monitoring sites is available online at: http://uk-air.defra.gov.uk/networks/network-info?view=nh3.

5.3 PRECIPITATION NETWORK (PRECIPNET)

Consisting of 38 sites (Figure 6) measurements of Na^+, Ca^{2+}, Mg^{2+}, K^+, PO_4^{3-}, NH_4^+, NO_3^-, SO_4^{2-}, Cl^- Within precipitation are made on a fortnightly basis, with two sites measured daily. The network sites are located near sensitive ecoystems and allows estimates of wet deposition of sulpher and nitrogen chemicals. The data for each of the monitoring sites is available online at: http://uk-air.defra.gov.uk/networks/network-info?view=precipnet.

5.4 NO_2 DIFFUSION TUBE NETWORK (NO2-NET)

Using 24 sites from PrecipNet (Figure 6) nitrogen dioxide measurements are made using diffusion tubes connected to the rain water collector stands. The diffusion tubes are exposed for 4-5 weeks at a time. The data for each of the monitoring sites is available online at: http://uk-air.defra.gov.uk/networks/network-info?view=no2net

5.5 ACID GAS AND AEROSOL NETWORK (AGANET)

Using the 30 locations from the National Ammonia Monitoring Network (NAMN) samples are collected monthly for gaseous HNO_3, SO_2, HCl and particulate NO_3^-, SO_4^{2-}, Cl^-, Na^+, Ca^{2+}, Mg^{2+}. gaseous SO_2 and particulate SO_4^{2-}. Data from the network, operational since 1999, is used to support pollution climate mapping and to calculate regional deposition budgets, especially in upland areas sensitive to acid deposition. The data for each of the monitoring sites is available online at: http://uk-air.defra.gov.uk/networks/network-info?view=aganet

5.6 UK ENVIRONMENTAL CHANGE NETWORK (ECN)

The Environmental Change Network (http://www.ecn.ac.uk/) is a multi-agency program sponsored by a consortium of UK government departments and agencies. Each organization contributes by either funding or carrying out the monitoring, with the data then pooled into the national ECN project. The ECN comprises of 12 terrestrial and 45 freshwater monitoring sites ranging from lowland to upland settings (Figure 8). Terrestrial sites include lowland grassland, agriculture, woodland, forest, upland and mountain monitoring locations and the freshwater sites are dominantly rivers and lakes. Each of the sites is monitored for a range of physical, chemical and biological variables all collected and analyzed in line with a series of national protocol documents (http://www.ecn.ac.uk/measurements).

5.7 UK UPLAND WATERS MONITORING NETWORK

The U.K. Upland Waters Monitoring Network was originally set up in 1998 under the name of the U.K. Acid Waters Monitoring Network (AWMN). The initial aim of the network was to assess chemical and biological changes of acidified lakes and streams to help provide data in response to the new UK emission laws. It has now been running for over 20 years and provides a valuable source of information for understanding current and predicting future trends.

The network consists of 26 sites across the UK, including headwater streams and lakes with monitoring focused at both biological and chemical parameters. Due to the upland focus of the network the majority of sites are located in Scotland (11) followed by England (6), Wales (4) and Northern Ireland (4), their locations are shown in Figure 9. Kernan et al. 2010 provide a useful review of the first 20 years of monitoring.

5.8 LARGE COMBUSTION PLANTS DIRECTIVE (LCPD)

Operators of power stations and refineries in England and Wales who have "opted in" to the Large Combustion Plants Directive (LCPD) were required by the Environment Agency to undertake "a monitoring program to assess changes in acidification and eutrophication deposition and ecological effects at appropriate Natura 2000 sites". In total 7 Natura 2000 sites are monitored for the effects of atmospheric deposition (

Table 7). The monitoring, that commenced in 2011 will form part of the operating permit improvement conditions for the plants (Monteith et al. 2012) with measurements including vegetation surveys, soil analysis and wet deposition analysis.

5.9 UK RESEARCH ON THE EUTROPHICATION AND ACIDIFICATION OF TERRESTRIAL ENVIRONMENTS (UKREATE)

The DEFRA and NERC co- funded UKREATE (UK Research on the Eutrophication and Acidification of Terrestrial Environments) project was used to collate evidence for the effects of nitrogen deposition on terrestrial habitats in the UK. The project is now finished however its output holds information on the field sites used in N deposition studies reported on in RoTAP (2012) and used in the data analysis for the JNCC reports (Stevens et al. 2011 and Emmett et al . 2011). A synthesis of the N-manipulation experiments can be found in Phoenix et al. (2012). The UKREATE website also holds a wealth of information http://ukreate.defra.gov.uk/index.htm

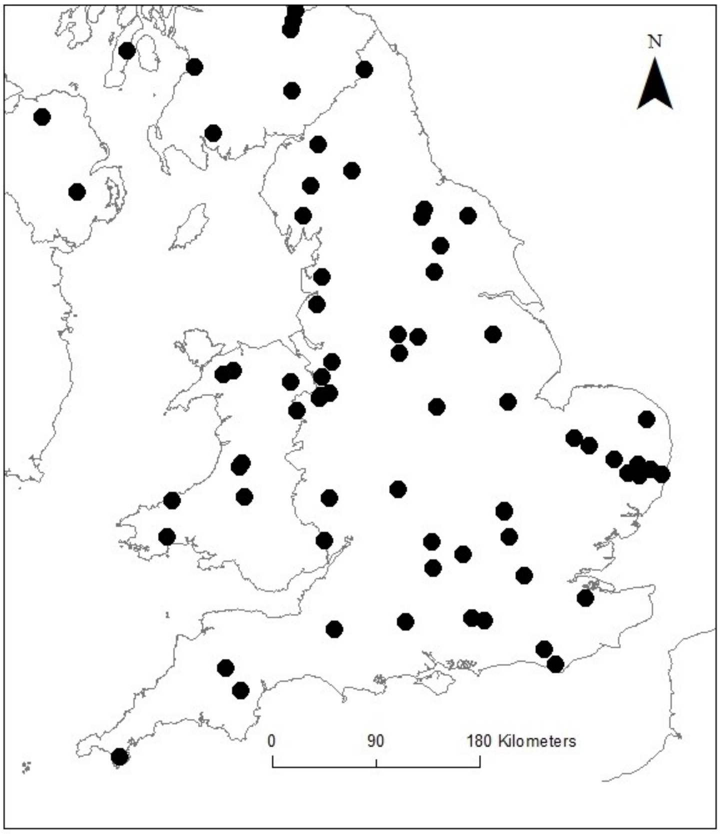


Figure 5 National Ammonia Monitoring Network (NAMN). *Contains OS data © Crown Copyright and database right [2015]*

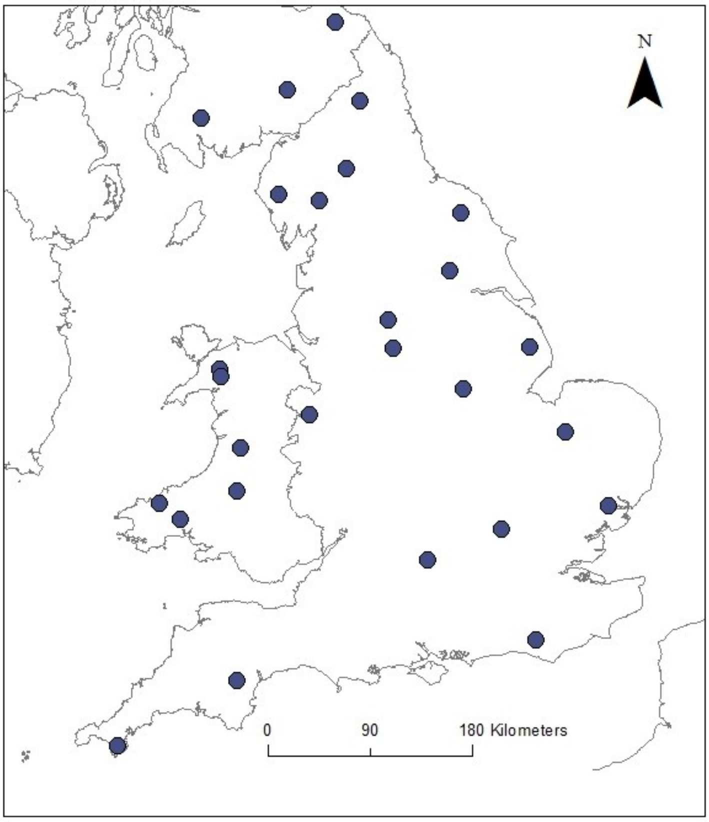


Figure 6 Precipitation Network and NO_2-net (PrecipNet & NO_2-net). *Contains OS data © Crown Copyright and database right [2015]*

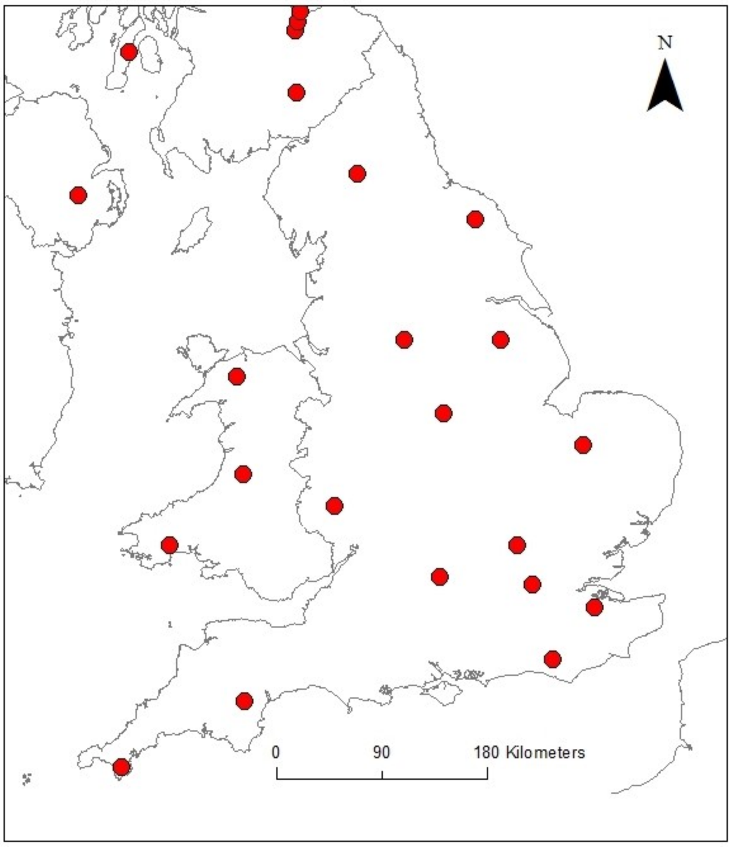


Figure 7 UK EAP Acid Gas and Aerosol Network (AGANet). *Contains OS data © Crown Copyright and database right [2015]*

	Species	**Frequency**	**Sites**	**Sampler**	**Analytical Techniques**
PrecipNet	Ionic composition of rain	Fortnightly	38	Bulk rain sampler	Ion chromatography ICP-OES pH Conductivity
Daily Wet only EMEP Supersites	Ionic composition of rain	Daily	1 (2)*	DWOC Sampler	Ion chromatography ICP-OES pH Conductivity
NO2-Net	NO_2 (g)	4-weekly	24	Diffusion tubes	Colorimetry
AGANet	**Gas phase:** HNO_3, SO_2, HCI (NH_3) **Particulate:** NO_3^-, SO_4^{2-}, CL^-, Na^-,Ca^{2+}, Mg^{2+} (NH^{4-})	Monthly	30	DELTA samplers	IC ICP-OES Selective Conductivity (AMFIA)
NAMN	NH_3 (g) NH^{4+} (g)	Monthly	85 30	DELTA and ALPHA samplers	Selected ion Conductivity (AMFIA)
PSNet	Sulphate	Daily	5	Stopped	n/a

*2 sites from 03/09

Table 3 Summary of UKEAP networks from Connolly et al (2011)

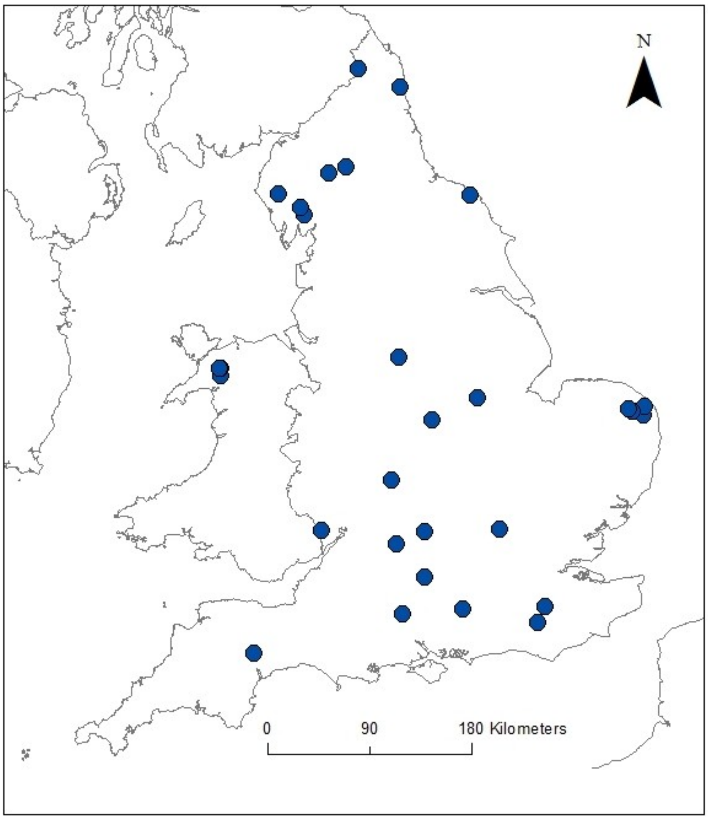


Figure 8 UK Environmental Change Network (ECN) terrestrial and freshwater sites. *Contains OS data © Crown Copyright and database right [2015]*

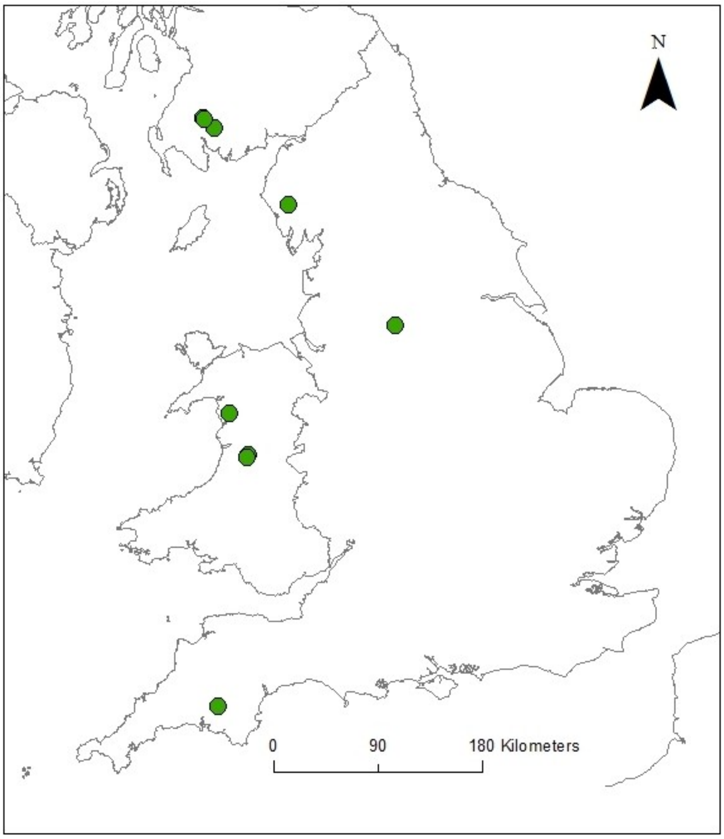


Figure 9 UK Upland Waters Monitoring Network. *Contains OS data © Crown Copyright and database right [2015]*

6. Trends for aerial deposition in the UK

RoTAP (2012) provides the most up to date synthesis of aerial deposition in the UK. Key findings in respect to long term monitoring and trends are summarized below. The work shows that there have been reductions in NO_x and NH_3 emissions, however the deposition of total nitrogen has not changed significantly during the last 20 years.

Emissions

- Emissions of nitrogen oxides (NO_x) in recent years have not reduced as much as policy-makers intended, decreasing by 58% between 1970 and 2010. The UK met the NECD target for 2010, with emissions 5% below the target value.

- Emissions of ammonia (NH_3) decreased by 21% between 1990 and 2010. The UK met the NECD target for 2010, with emissions 4% below the target value.

Concentration and deposition

- Concentrations of oxidised nitrogen in surface air (as nitrogen dioxide) have declined approximately in line with emission reductions (Figure 10)

- Concentrations of reduced nitrogen (as ammonia) have changed little since 1990 (Figure 11), with small increases in background areas and small reductions in regions dominated by pig and poultry sources. This is due to complexities regulating emissions from agriculture.

- The total deposition of nitrogen (including both oxidised and reduced forms) in the UK **has not changed significantly** remaining almost the same (between 350-400kt-N per year) between for the last 20 years, RoTAP (2012)

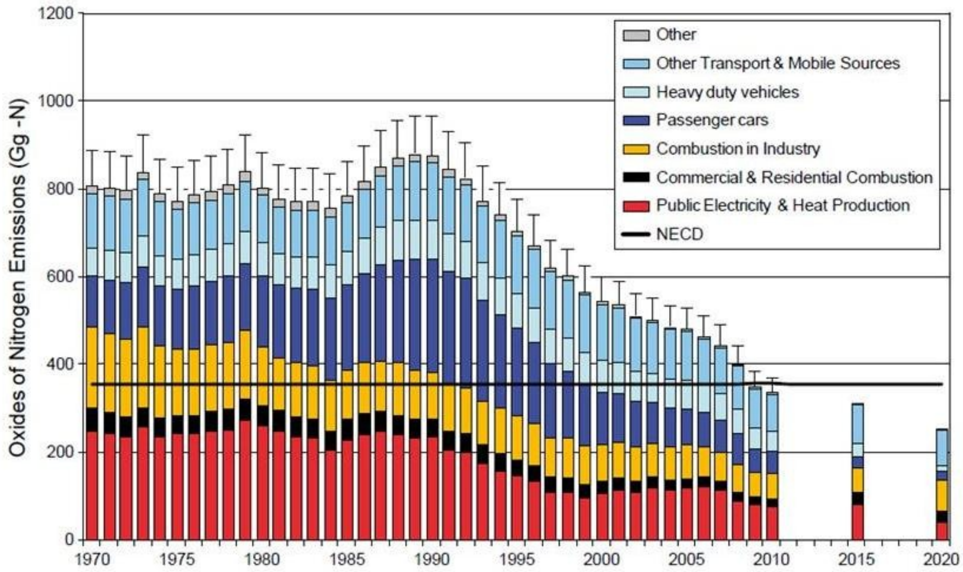


Figure 10 UK emissions of NOx – N (Gg-N) (Defra, 2011; EIONET, 2012), projections based on the UEP38 energy scenario. Graph from RoTAP, 2012.

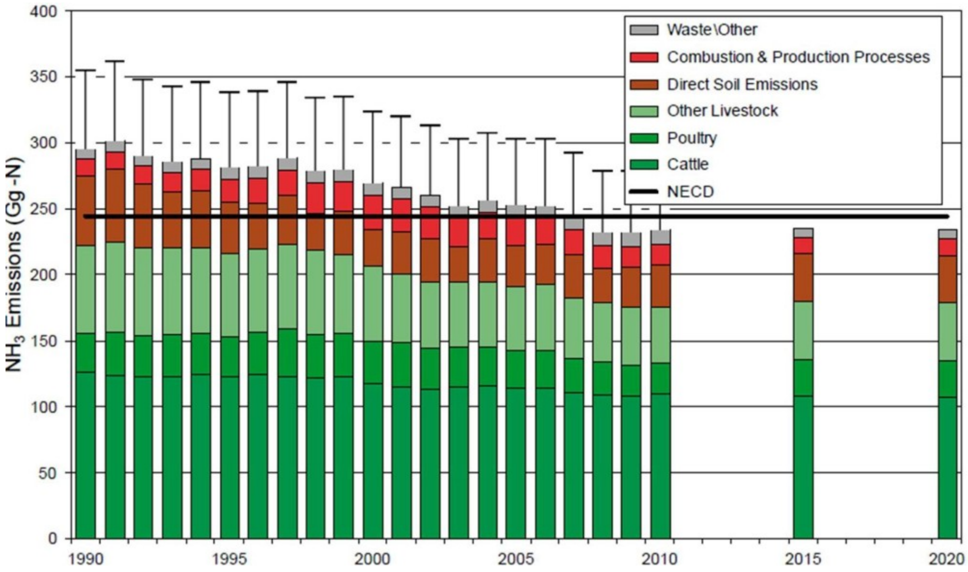


Figure 11 UK emissions of NH_3 (Gg-N) (Defra, 2011: EIONET, 2012), based on the UEP38 energy and 'business as usual' agriculture scenarios. From RoTAP,2012.

7. Existing monitoring protocol and knowledge gaps

Protocols for the monitoring of Natura 2000 sites in response to the LPCD have recently been agreed between the regulatory and conservation bodies in England and Wales (Monteith et al. 2013a & b). Key points from the methodologies are summarised below and it is suggested that any further work as part of this project should be undertaken in line with existing and approved methodologies.

In response to permitting under the LPCD (Large Plant Combustion Directive) (Monteith et al. 2013a) ensured an agreed protocol for ecological and deposition monitoring at Natura 2000 sites has already been agreed by the regulatory bodies in England and Wales. Any proposed protocol should be reconsidered following more recent information and evidence.

The protocol covers the installation of deposition monitoring equipment including; bulk rain gauges for anion, cation, pH, specific conductivity and ammonium and phosphate testing. Field measurements and sample analysis for, gaseous concentrations including suplhur dioxide (SO_2), nitrogen dioxide (NO_2) and nitric acid (HNO_3), soil solution chemistry and associated meteorological monitoring including precipitation and wind direction.

The protocol for ecological survey (Monteith et al. 2012b) required site selection based on vegetation homogeneity of the area with preference given to sites where vegetation varied over the survey area of 1-2 hectares, ease of access and the likelihood of land management changes over the next four years. The site security was also assessed as the deposition monitoring equipment would need to be located in the vicinity. The vegetation survey plot 100m x 100m was divided into 2 x 2m squares. A randomised plotting programme allowed the selection of 50 monitoring points within this area that were surveyed for both higher and lower plants. It is not known if concerns raised by Emmett et al. (2011) about the suitability of the CSM (common standards monitoring) approach have been taken into account, if not this should be considered for any vegetation monitoring undertaken as a result of this project. Source apportionment studies would benefit from using the same or comparable methodologies to previous work to allow direct comparison between source apportionment studies.

Figure 12 Vegetation monitoring in Cannock Chase (SSSI) using an agreed methodology to assess the effects of atmospheric nutrient deposition (from Monteith et al 2013b).

8. Nitrogen budgets and source attribution studies

Nitrogen Budget

Nitrogen budgets for GWDTE must include both atmospheric wet and dry deposition and terrestrial pathways such as groundwater and surface water. It may also be necessary to monitor fluxes from a wetland to quantify if the site is a source or sink for nitrogen (e.g. Lohila et al. 2010). Substantial monitoring programs are required to quantify the loading from a combination of nutrient pathways. Factors that influence the accumulation of nitrogen must also be considered such as vegetation and soil cover.

It is important to have an advanced hydrological conceptual model of any GWDTE in order to quantify the loading of nitrate from groundwater and surface water pathways. A poor understanding of the hydrology of any given site will result in knowledge gaps when it comes to quantifying the input from the hydrological system against that from atmospheric deposition. Jones et al. (2005) undertook a nitrogen budget for a dune site including humid dune slacks in South Wales (Merthyr Mawr) measuring atmospheric deposition of dry and wet atmospheric in puts, including dry gaseous deposition of NH_3 and estimating inputs of groundwater NO_3 entering the site via limestone streams over a 12 month period. , However a limited understanding of the hydrogeological regime of the site was stated as a knowledge gap in understanding. A nitrogen budget has also been conducted for Newborough Warren, investigating the impact of NH_3 emissions from the nearby poultry unit (Jones et al. 2013). The study showed that contributions from this point source caused critical load exceedance within the dune site, and contributed 30% of the atmospheric deposition load. The variety and quality of humid dune slacks comprise some of the key qualifying features for this SAC. Additional research at the nearby dune system of Aberffraw has specifically addressed groundwater N concentrations and impacts on the biological condition of the site (Rhymes et al. 2014). That study showed adverse impacts on vegetation composition at low levels of groundwater nitrate input, below current GWDTE guidelines for dune slacks. Atmospheric inputs have not been assessed, but could be derived from calculations at Newborough Warren. Environment Agency Wales (2005) produced a source apportionment study at Crymlyn Bog, South Wales. The report noted that where regulated activities only contribute to a small percentage of total atmospheric deposition (i.e there are other sources that are not regulated) then regulatory action on its own is unlikely to succeed.

Source attribution

Source attribution is the estimation of the contribution by different sources (atmospheric or terrestrial) to pollution, in this example the nitrogen budget of a GWDTE. **Very few studies have assessed impacts from atmospheric and surface or groundwater inputs at the same site in the UK and this presents a major knowledge gap**. Source apportionment studies can be divided into two approaches: load orientated approach and the source orientated approach (EEA, 2005). The load orientated approach and the source orientated approach are similar but differ in their approach to estimating the input from diffuse sources. Both the load orientated and source orientated approaches were used by the EEA to estimate nutrient inputs to river catchments and coastal areas, rather than individual wetland sites.

Existing source attribution model for atmospheric deposition in the UK

Source apportionment data (and concerns) is available for all of the U.K. SACs, SPAs and SSSIs through APIS (www.APIS.ac.uk). The APIS website allows the user to look up national-scale nitrogen deposition for selected interest features at any given SAC, SPA or A/SSSI. Deposition data for 2005 based on the CBED methodology is used together with and a forecast for the year 2020 (UEP30 scenario) generated by the FRAME (Fine Resolution Atmospheric Multi-pollutant Exchange) model. This model was applied to assess the magnitude and spatial distribution of nitrogen and sulphur from 156 different point and background sources. The outputs from the APIS website are in a pie chart format (Figure 13) and can be produced for the emissions data year 2005 or for a future emissions scenario year (2020). The APIS website informs the user that both are now out of date.

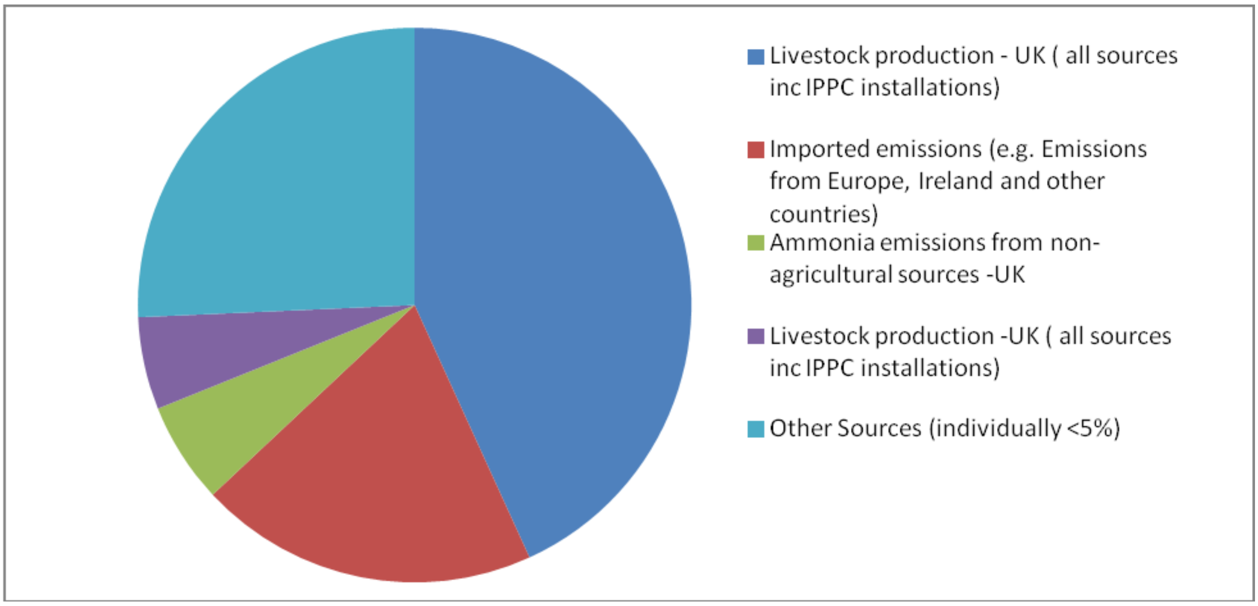


Figure 13 Pie chart describing nitrogen source attribution for a wetland based on the 2005 dataset (www.apis.ac.uk)

Difficulties may arise when quantifying the input of diffuse and point sources into the total nitrogen budget of a site and a detailed understanding of the hydrology of the GWDTE would be required. Although the EEA report focuses on source apportionment for the aquatic environment it has several recommendations that would be directly applicable to any studies at GWDTE including the need for more:

- Data to quantify annual discharges from point sources (e.g sewage systems)
- Data to quantify annual retention within the wider hydrological cycle
- Information on groundwater residence time and degradation of nitrogen within aquifers
- Information on agricultural practices to allow development of models for nutrient loss

9. Spatial analysis of critical loads and threshold values

9.1 METHODOLOGY

For the first time the results of the WFD chemical classification, incorporating threshold values (TV), wetland habitat condition and atmospheric nitrogen critical loads (CLnutN) exceedances are considered together.

The agreed methodology is a spatial analysis of several key datasets (listed below). The aim was to see where CLnutN for atmospheric nitrogen deposition and TV for groundwater were both exceeded at the same sites, thus suggesting multiple pathways for nutrients to a GWDTE. We are also interested in areas where GWDTEs exceed their CLnutN from atmospheric deposition and the impact this may have on the WFD groundwater body classification. For instance could 'we' be pointing the finger at nutrient pressures in groundwater when actually atmospheric deposition is playing a key role in the significant damage of many GWDTE.

The following text describes the geospatial datasets used for the spatial analysis:

GWDTEs: The list of GWDTE was agreed for the WRD classification work by CCW (now NRW) and NE ecologists along with colleagues in the EA. Guidance in UKTAG, 2012a was used to help delineate wetlands that could be considered to be groundwater dependent. Of the 3320 GWDTE in England and Wales 2508 have an EU designation (i.e SAC, RAMSAR, SPA) the remaining 812 are non EU designated sites (e.g. LNR, SSSI). It is useful to note that even when a site is classified as 'non designated' it can still support examples of Annex 1 habitats – which in turn are reported for the Habitats Directive Article 17

WFD Classification results and threshold values: The results from the WFD chemical classification were supplied by the EA and NRW, with a final status (good or poor chemical status) attributed to every groundwater body in England and Wales. It was possible to query each of the 6 individual tests that are involved within the overall chemical assessment including the GWDTE test (see UKTAG, 2012b). The GWDTE test incorporated the recently defined 'threshold values' (UKTAG, 2012a) with a score of 0-3 being applied to all 3320 GWDTE in this analysis.

The scores are as follows:

0 (NO)	Threshold value has not been reached within the groundwater body. This applies to 1277 sites.
1 (NO)	Threshold value has been exceeded as a groundwater body average and or at one monitoring point within 5km of the GWDTE, or a NEAP N loading assessment indicated a high nitrate loading. This applies to 1929 sites.
2 (NO)	Threshold predicted to exceed level by 2027. This applies to just 7 sites.
3 (YES)	Threshold exceeded a local monitoring point with high connectivity to the GWDTE. This applies to 107 sites.

Wetland Condition and NVC mapping

All of the EU designated sites have condition data (favourable – unfavourable etc) in total 2084 sites have condition data and 1236 have no condition data.

Critical Loads

Critical Loads have been assigned to the designated feature habitats of the SSSIs that correspond to or are co-located with GWDTEs (See Section 4). N deposition (NOx + NHx) values have been assigned to each SSSI by two methods: (a) extracting the value for a single point within each SSSI (b) calculating an area-weighted average value for the SSSI. In both cases the CBED 5x5km annual average deposition data for 2010-12 were used. Critical load exceedances were calculated for each feature habitat and the maximum exceedance per site derived for the results presented below. It should be noted that some features within the SSSIs may be less sensitive to nitrogen and have higher critical loads and lower exceedance values, or not be exceeded. The use of the maximum exceedance is a precautionary approach.

The abbreviations used in the GIS dataset are provided below for reference. Where a critical load has not been assigned, a value of -9999 is recorded for data analysis purposes. When deposition is below the critical load then a negative value is reported; positive exceedance values indicate the critical load has been exceeded by nitrogen deposition.

MaxOfRecCLexc_pts_kg: maximum exceedance of recommended nutrient N critical loads by N deposition for single point within each site in kg N ha^{-1}year^{-1}

MaxOfRecCLexc_awtd_kg: maximum exceedance of recommended nutrient N critical loads by area-weighted N deposition for each site in kg N ha^{-1}year^{-1}

-9999	This means no critical load value assigned to any features on the site. This applies to 965 sites
0	A score of zero means the nitrogen deposition is below the critical load(ie, critical load not exceeded). This is also represented by negative exceedance values <0.0 (and greater than -9999). This applies to 226 sites.
1	A score of 1 indicates that the nitrogen deposition is greater than the critical load (ie, the critical load is exceeded). This is also represented by positive exceedance values. This applies to 2129 sites.

The scores for the TV and CL are combined to give an overall score.

Site Score	Explanation	WFD TV excedance	CL excedance	No of sites by site_score_pt	No of sites by site_score_awtd
-9999	TV not exceeded and no CL assigned	NO	-9999 (i.e no CL)	949	949
0	Neither TV or CL exceeded	NO	0	222	219
1	TV exceeded but CL not exceeded	YES	0	4	4
1	TV exceeded but no CL assigned	YES	-9999 (i.e no CL)	16	16
2	Only CL exceeded	NO	1	2042	2045
3	Both TV & CL exceeded	YES	1	87	87

9.2 RESULTS: COMPARISON OF CL, TV AND HABITAT CONDITION

Before any spatial analysis was performed a comparison was undertaken to quantify the number of sites that exceeded the CL or the TV and how this applied to their habitat condition (Table 4 Table 5 and Table 6), unfortunately habitat condition was only available for England.

The analysis does not show similar trends in England and Wales, this is due to the inclusion of a large number of non designated sites in Wales that have not been assigned a critical load. The majority of sites in England and Wales (if you consider the 872 non designated sites in Wales with no CL) have nitrogen deposition above the critical loads however far fewer exceed their groundwater threshold values.

From this analysis it would appear that excedance of CL are far more common than the excedance of a TV, this **analysis should be interpreted with caution** for the following reasons:

(i) The CBED deposition provides national coverage and therefore every site can be assigned a deposition value, and exceedances calculated for each feature habitat (for which critical loads are available). In addition, as mentioned above, critical loads and exceedances may vary between features within an individual site, and while some may not be exceeded, the most sensitive feature habitats have lower critical loads and are widely exceeded by current levels of N deposition. The analysis presented here does not take into account which habitat features are exceeded or not, it simply uses the maximum exceedance per site.

(ii) TVs rely upon NEAP N modelled data and real data collected from a monitoring point considered to be in hydraulic connection with the GWDTE. Critically the groundwater data has not been modelled across the country and thus it is only possible to assign values where there is 'real' data. The scoring for the WFD classification process is slightly less 'black and white' with four possible categories (see 9.1 Methodology). In this analysis only GWDTEs that score 3 i.e where the TV is exceeded at a local monitoring point, have been considered to be truly in excedance of their threshold value.

However, it is worth noting (i) exceedance of critical loads does not necessarily equate with current damage or impacts; but does indicate that adverse impacts are expected to occur. (ii) CSM may substantially under report impacts due to N deposition as CSM was not designed for monitoring N deposition impacts (e.g. Williams, 2006).

	No of GWDTE in England	**>CLV**	**< CLV**	**NO CLV**	**> TV**	**< TV**	**>CLV & >TV**
No of GWDTE	**2084**	1770	224	90	84	2000	79
% of total GWDTE in England	**100**	**85**	**10**	**5**	**4**	**96**	**4**

Table 4 Comparison of the CL and TV for (n2084) GWDTEs (SSSIs) in England only.

	No of GWDTEs in Wales	**>CLV**	**< CLV**	**No CLV**	**> TV**	**< TV**	**>CLV & >TV**
No of GWDTE	**1236**	359	3	872	23	1213	8
% of total GWDTE in Wales	**100**	29	0.2	71	2	98	0.6

Table 5 Comparison of the CL and TV data for (n1236) GWDTEs (SSSIs) in Wales only. No condition assessments were supplied.

England	**Wales**	
85 %	**29 %**	**GWDTEs exceed their CLV**
4 %	**2 %**	**GWDTEs exceed their TV**
4 %	**0.6 %**	**GWDTEs exceeded both the CLV and TV**
England and Wales		
66.1 %		**GWDTEs exceed their CLV**
3 %		**GWDTEs exceed their TV**
3 %		**GWDTEs exceeded both the CLV and TV**

Table 6 Summary of excedance of CL and TV in both England and Wales separately and combined, for the list of (n 3320) GWDTEs.

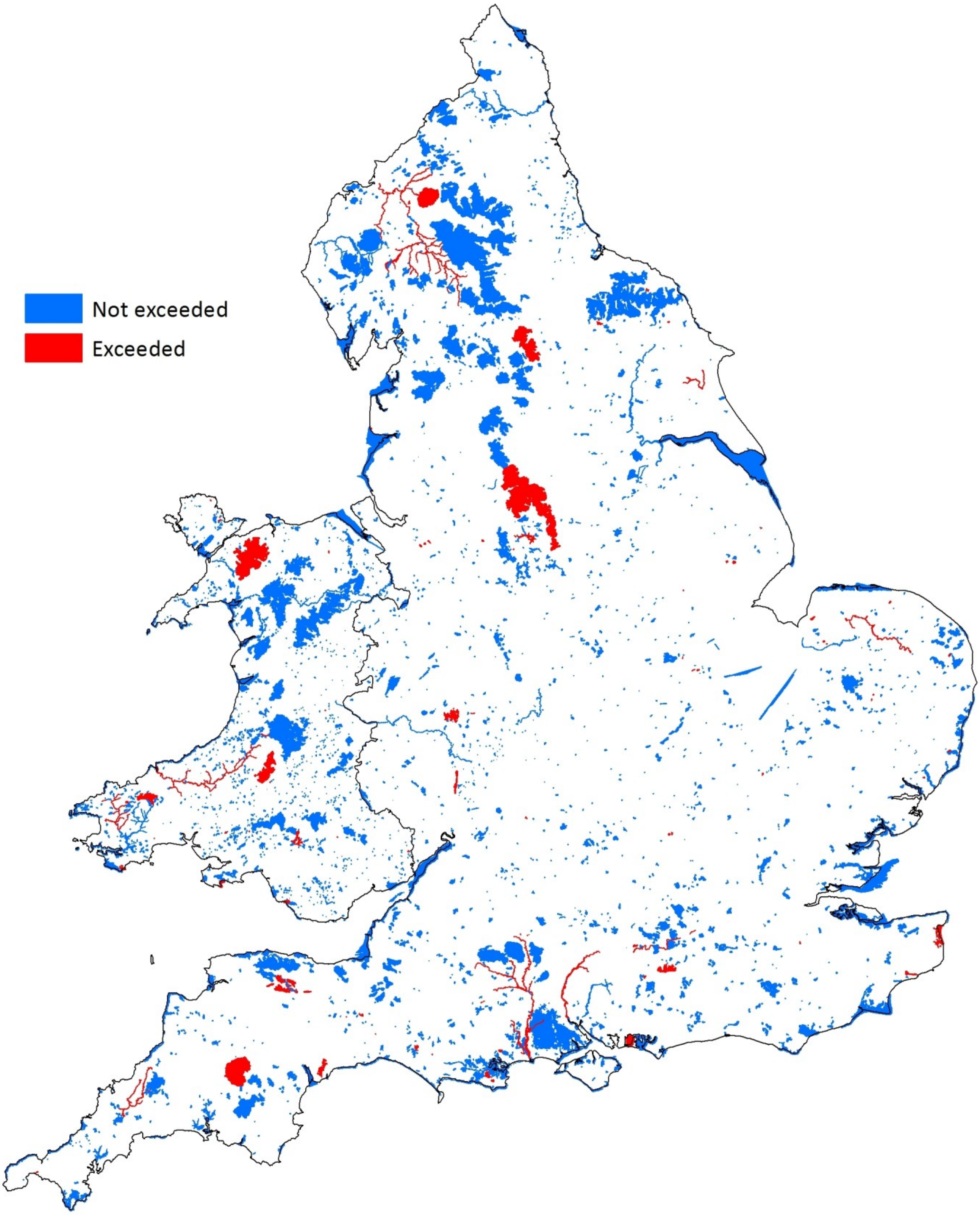
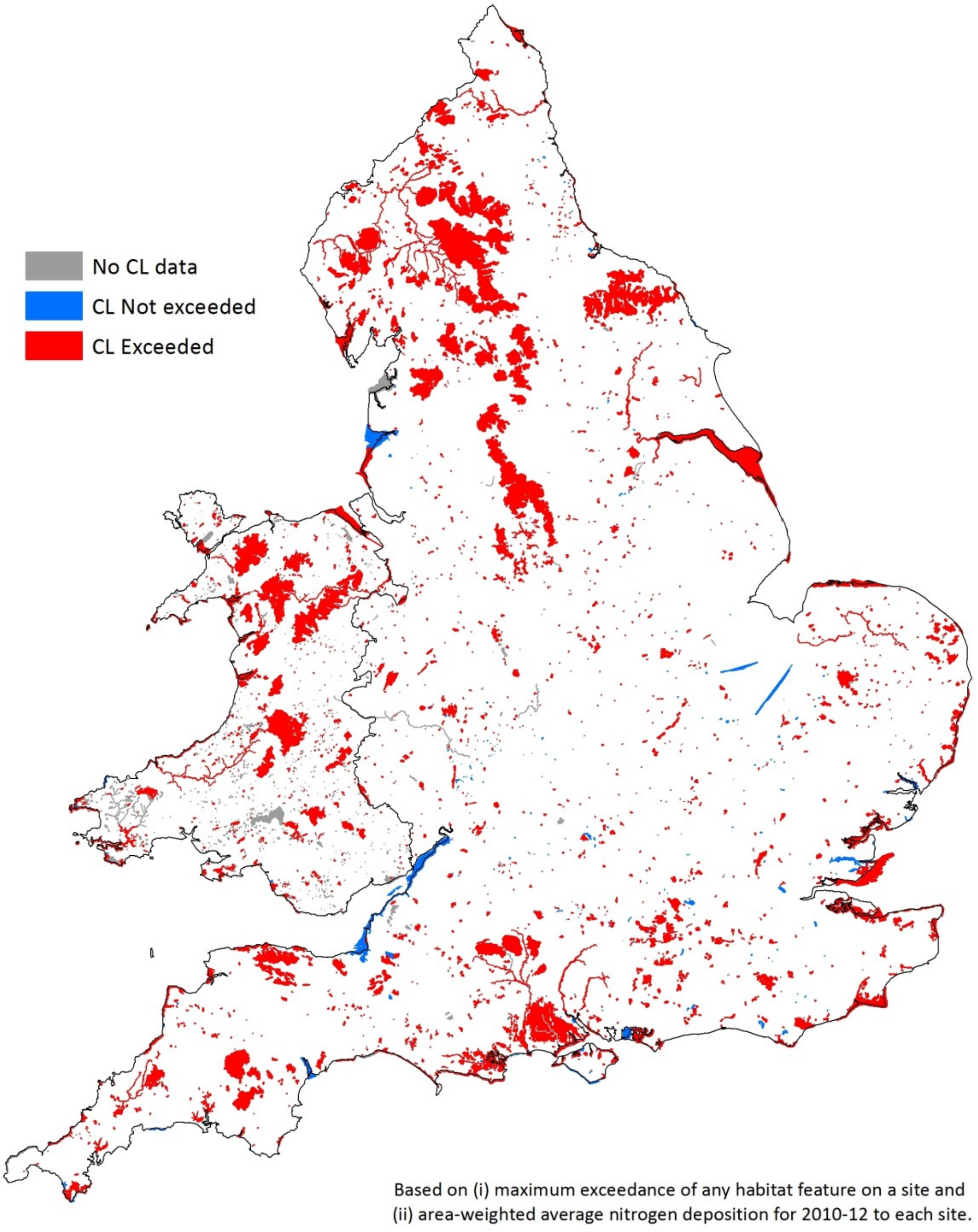
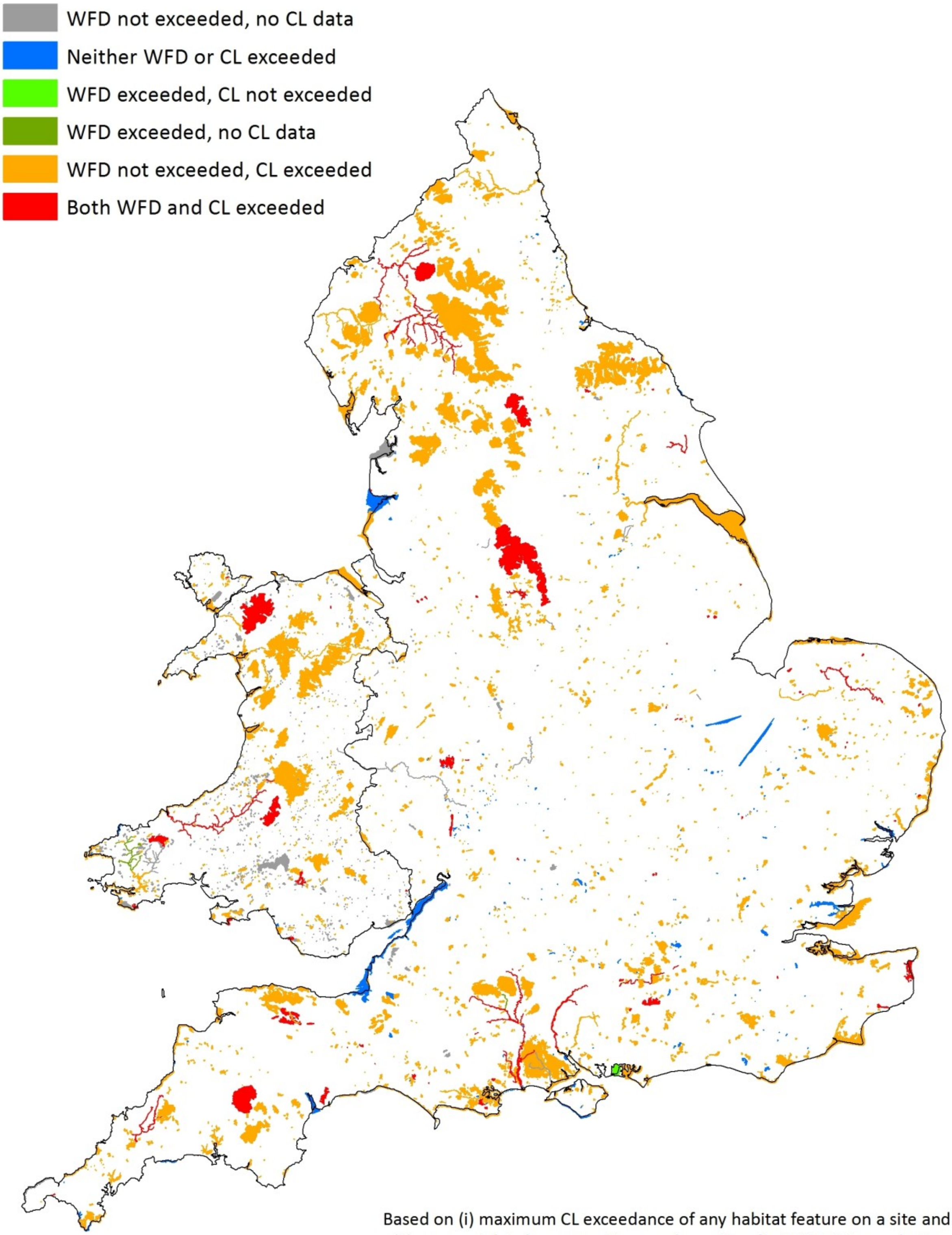


Figure 14 Water Framework Directive ‘threshold value’ results (Exceeded = score of 3, not exceeded = score <3). *Contains OS data © Crown Copyright and database right [2015]*



Based on (i) maximum exceedance of any habitat feature on a site and
(ii) area-weighted average nitrogen deposition for 2010-12 to each site.

Figure 15 Exceedance of nutrient nitrogen critical loads by CBED total nitrogen deposition for 2010-12; results are based on the maximum exceedance for any feature habitat within each SSSI in England and Wales. (exceeded = score of 1, not exceeded = score 0). *Contains OS data © Crown Copyright and database right [2015]*



Based on (i) maximum CL exceedance of any habitat feature on a site and (ii) area-weighted average nitrogen deposition for 2010-12 to each site.

Figure 16 Map showing excedance of nitrogen critical loads and Water Framework Directive threshold values. Exceedance of nitrogen critical loads based on CBED deposition for 2010-12 and maximum exceedance for any habitat feature per site (SSSI) in England and Wales. *Contains OS data © Crown Copyright and database right [2015]*

9.3 IMPLICATIONS FOR WFD AND EFFECTIVE CATCHMENT MANAGEMENT

Water Framework Directive

The results show that 85% of GWDTEs in England and 29% in Wales assessed as part of the WFD classification exceed the nitrogen critical load for at least one feature habitat within a site (SSSI). This figure for Wales should be larger however the inclusion of a large amount of non designated sites without critical load values resulted in a lower percentage failing their critical load.

- The low percentage of sites exceeding their groundwater TV (3%) is most likely a reflection of the lack of chemical nutrient data from WFD monitoring at or near GWDTE within this study.

- There is a need for the collection of more water chemistry data at or in WFD monitoring points linked to GWDTEs. This would provide vital data for the future classification of GWDTEs in England and Wales against existing threshold values.

- Localised nutrient enriched waters, e.g. agricultural surface runoff, are known to have significant impacts along the periphery of GWDTEs. This localised pressure is often not reflected in the WFD classification process. One positive is that land management agreements targeting adjacent fields may offer very effective solutions to tackle nutrient enrichment when the source and pathway of nutrients can be shown to be from adjacent fields.

- The critical load information should be included within future WFD classification so that future assessments consider atmospheric loading in conjunction with terrestrial loading

- It is possible that many GWDTEs are in poor condition primarily due to atmospheric deposition, however a greater understanding of the source and fate of nutrients in wetlands is needed before any such conclusion can be drawn.

- The widespread excedance of critical loads reported in this preliminary study supports the need for detailed source apportionment studies at GWDTEs. Defining the sources and pathways for nutrients will support regulatory bodies with implementing targeted and effective WFD programs of measures.

Effective catchment management

- The results show that 64% (this includes the non designated sites with no critical load) of the GWDTEs in England and Wales exceed the critical load for at least one habitat feature (though habitat type not taken into account in this study), suggesting that effective catchment management, may in some cases only be part of the solution, and that regulation of emissions from industry and agriculture may be required to help GWDTEs achieve favourable status.

- Regulation and management of nutrient application and water management within fields immediately adjacent to many GWDTEs (for example see Anglesey and L lyn Fens SACs) could also offer a simple and effective solution to reduce localised terrestrial sources and pathways of nutrients.

  It is possible to regulate point source emissions (e.g factories) however the contribution of diffuse, and perhaps unregulated, nitrogen to the loading at a GWDTE may be very challenging to regulate.
- There still exists much uncertainty about the relative contribution and fate of terrestrial and atmospheric nutrient loading at GWDTEs. With this uncertainty comes a reduced ability to successfully mitigate against these pressures.

- There is a need to define a defensible methodology to quantify nitrogen loading (source apportionment) both at GWDTEs and potentially within entire groundwater bodies. Defining the sources and pathways for nutrients will allow targeted and effective WFD programs of measures to be undertaken.

10. Identification of potential study sites

10.1 EXISTING CASE STUDIES FROM THE UK

Several GWDTEs in England and Wales are part of a suite of various monitoring programmes set up to assess the impact of atmospheric deposition at designated sites. This section will provide a list of GWDTEs in England and Wales that are part of monitoring networks or have undergone research in the past aimed principally at atmospheric deposition. The list (Table 7) also included references to the data sources and to any existing hydrogeological conceptual models. A list of GWDTEs that have exceeded both their TV and CL are included in (Appendix 2). The aim is to provide a short list of GWDTEs that have existing atmospheric deposition data that could be used for future projects.

SSSI	Habitat	Summary of Project	Hydrological Conceptual Model	Data Source	Location
Thorne, Crowle & Goole Moors	Degraded Raised Bogs & Active Raised Bogs	Large Plant Combustion Directive (LCPD)		Monteith et al. 2012	England
Cannock Chase	European dry heaths	Large Plant Combustion Directive (LCPD)	Some hydrogeological data	Monteith et al. 2012	England
The New Forest	European dry heaths	Large Plant Combustion Directive (LCPD)		Monteith et al. 2012	England
Skipwith Common	MG16 heathland	Large Plant Combustion Directive (LCPD)		Monteith et al. 2012 & Emmett et al. 2011& Penny Anderson, 2008	England
Astley & Bedford Mosses	Degraded Raised Bogs	Large Plant Combustion Directive (LCPD)		Monteith et al. 2012	England
Minsterley meadows	MG5 grassland	CSM monitoring and grass forb ration v atmospheric deposition near poultry farm	No but Adjacent to small metal mine (EA)	Emmett et al. 2011	England
Moor House	M18b M19a/b blanket bog	Environmental Change Network (ECN)		Emmett et al. 2011	England
North Wyke	Lowland grassland	Environmental Change Network (ECN)		Emmett et al. 2011	England
Porton	Woodland and semi natural chalk grassland	Environmental Change Network (ECN)		Emmett et al .2011	England
Budworth Common	Lowland heath	N budget, N immobilization is soil pools and leaching loss. Management cut and re establishment monitored		UKREATE.defra.gov.uk	England

SSSI	Habitat	Summary of Project	Hydrological conceptual Model	Data source	Location
Wardlaw Hay Cop	Calcaerous and acidic Grassland	Long term 18 year study application of N and P		UKREATE.defra.gov.uk	England
Peaknaze	Upland moorland	Impact of climate change under reduced pollution effects		UKREATE.defra.gov.uk	England
Ainsdale dunes and sands	dune grassland and humid dune slacks	Environmental Change Biodiversity Network	Clarke and Sanitwong Na Ayuttaya (2010)	Emmett et al. 2011	England
Bure Marshes	fen (flood plaine basic) wet woodland open water	Environmental Change Biodiversity Network		Emmett et al. 2011	England
Burnham Beeches	Beech woodland, dry and wet heath	Environmental Change Biodiversity Network		Emmett et al. 2011	England
Fens Whixhall & Bettisfield Mosses	active raised bog, degraded raised bog	Environmental Change Biodiversity Network	Yes	Emmett et al. 2011	England
Ingleborough	upland wet and dry heat bog	Environmental Change Biodiversity Network		Emmett et al. 2011	England
Lindisfarne	mobile dunes, humid dune slacks, heath and grassland	Environmental Change Biodiversity Network		Emmett et al. 2011	England
Thursley	lowland heath and valley mire	Environmental Change Biodiversity Network N additions and changes in management and monitored recovery		Emmett et al. 2011	England
Newbald Becksies and Askham Bogs	various	Potential impact of historic atmospheric deposition from power stations	Paul Howlett, Environment Agency	Paul Howlett, Environment Agency, Hogg et al 1995	England
Wye Valley SAC		Suggested by Andrew Pearson EA			England
Merthyr Mawr	Humid dune slacks	Nitrogen Budget	SWS, 2010a	Jones et al. 2005 Jones et al. 2006	Wales
Mynydd Llangatwyg	Blanket Bogs	Large Plant Combustion Directive (LCPD)		Monteith et al. 2012	Wales
Esgryn Bottom	Active Raised Bogs	Large Plant Combustion Directive (LCPD)		Monteith et al. 2012	Wales
Cors Caron	Raised Bog	Environmental Change Biodiversity Network 5 years of PC bulk data, 13 months of NH3 diffusion tubes	Rigare	NRW data	Wales

SSSI	Habitat	Summary of project	Hydrological conceptual model	Data source	Location
Cors Erdderiniog	Fen	Environmental Change Biodiversity Network 5 years of PC bulk data, 13 months of NH3 diffusion tubes	SWS, 2010b and Rigare (assorted dates)	NRW data	Wales
Cors Fochno	Raised bog	Environmental Change Network (ECN) 5 years of PC bulk data, 13 months of NH3 diffusion tubes	Rigare reports for NRW	NRW data	Wales
Yr Wyddfa	acidic grassland and heath	Environmental Change Network (ECN)		Emmett et al. 2011	Wales
Rhuabon Moor	Moorland	Impacts of nitrogen, management and intervention on moorland. Application of N and P.		UKREATE.defra.gov.uk	Wales
Pwllpeiran	Acidic grassland and heath	Nitrogen addition experiments to determine interaction between grazing pressure and nitrogen deposition		UKREATE.defra.gov.uk	Wales
Cwm Cadlan	wet calcaerous grassland	Environmental Change Network (ECN)		Emmett et al. 2011	Wales
Newborough Warren	dune grassland and humid dune slacks	Environmental Change Network (ECN); impacts of nitrogen management and intervention; chronosequence studies. Nitrogen budget. Source apportionment for local NH3 atmospheric sources.	Numerous reports e.g. Stratford , 2006	Emmett et al. 2011 NVC maps 1980s and 1990s; Jones et al. 2008; Plassmann et al. 2009; Jones et al. 2013.	Wales
Ogof Ffynnon Ddu	limestone pavements and cave system	Environmental Change Network (ECN)	No	Emmett et al .2011	Wales
Oxwich	Humid dune slacks	Environmental Change Network (ECN)	Grey literature held by NRW	Emmett et al. 2011	Wales
Rhos Llawr Cwrt	bog grassland oak woodland	Environmental Change Network (ECN)		Emmett et al . 2011	Wales
Crymlyn Bog	Quaking bog transition mire alkaline fen	Nutrient Source Apportionment study	Grey literature held by NRW	Environment Agency Wales, 2004 & 2005. Headley, 2004.	Wales

Table 7 GWDTEs in England and Wales that have historic or current atmospheric deposition data/monitoring programmes

10.2 Selection of potential study site for Phase 2 investigation

No strict methodology has been applied to proposing potential sites for the phase 2 work, however the following points have been considered;

- Is there an existing conceptual model for the site?
- Is there NVC data for the site?
- Is there existing on site water level and quality data?
- Has the critical load or threshold value been exceeded?
- What is the distance to an established atmospheric chemistry monitoring station?
- Do the sites present variability in terms of type and setting?
- Are there willing local experts who will assist with future investigations?

Potential sites are listed in (Table 8)

GWDTE	Country	Type	Setting	WFD Threshold Value	Critical Load	Conceptual Model	NVC data	Distance to existing atmospheric monitoring point
Wynunbury Moss	England	Lowland bog	Lowland	Not exceeded	Exceed	Yes	Yes	20 km
Fens Whixhall & Bettisfield Mosses	England/ Wales	Fens	Lowland	Not exceeded	Exceed	Yes	Yes	On site
Newbald Becksies	England	Base rich marsh and wet natural grassland	Lowland	Not exceeded	Exceed	Yes	Yes	>50 km
Askham Bogs	England	Riased bog and fen	Lowland	Not exceeded	Exceed	No	Yes	10 km
Merthyr Mawr	Wales	Humid Dune	Lowland coastal	Exceed	Exceed	Yes	Yes	>50 km*
Newborough Warren	Wales	Humid Dune	Lowland coastal	Not exceeded	Exceed	Yes	Yes	>50 km*
Aberffraw	Wales	Humid Dune	Lowland coastal	Not exceeded	Exceed	Yes	Yes	>50 km*
Cors Bodeilo & Cors Eddreiniog	Wales	Alkaline and Calcareous Fens	lowland	Exceed	Exceed	Yes	Yes	>50 km
Cors Carron (Tregaron Bog)	Wales	Riased Bog	Upland	Not exceeded	Exceed	Yes	Yes	<10 Km

Table 8 Possible sites for consideration in phase 2.

* Nitrogen budget for atmospheric deposition available.

11. Design of monitoring network

11.1 PARTNERSHIP WORKING

The monitoring program should be designed and implemented with full consultation of all partners, including, but not limited to: Environment Agency, Natural England, Natural Resources Wales, British Geological Survey, Centre for Ecology and Hydrology, PLINK network and SEPA.

11.2 POTENTIAL RESEARCH HYPOTHESIS

The following are key questions that we aim to answer:

- **How successfully can a nitrogen budget and source apportionment (including both atmospheric and terrestrial sources) be defined for any given wetland?**

  how will this help both our understanding of nutrient sources and pathways, management of wetlands in unfavourable condition and subsequent WFD classification and program of measures?

- **Is it possible to quantify the input of atmospheric deposition to any given habitat, both directly and as an indirect contribution via groundwater and surface water inputs?**

  how will this help our understanding of nutrient pathways for atmospherically derived nutrients, management of wetlands that exceed their critical load and subsequent WFD classification and program of measures?

- **At a site level is it possible to identify the main pressure contributing towards unfavourable condition between atmospheric deposition, terrestrial nitrate and poor site management?**

  what are the implications for the Water Framework Directive classification process and future site management to achieve favourable condition?

11.3 EXISTING DATA

As a minimum the following data should be obtained as part of a desk top study before any new studies are undertaken:

Ecological

- NVC mapping
- CSM data, ideally botanical quadrat data to inform calculation of plant-based damage metrics.
- Expert local knowledge , both ecological and hydrological

Hydrological

- Hydrogeological conceptual model and/or water balance
- Surface water and groundwater quality
- Surface water and groundwater levels
- Rainfall and rainwater quality
- Expert local knowledge

Atmospheric

- Data from existing atmospheric deposition monitoring networks
- Modeled atmospheric deposition data
- Expert local knowledge

11.4 EQUIPMENT

The following is a list of equipment, suppliers and costs (correct at time of writing) for analysis and sample equipment that may be required for site investigation. Where one of the potential partners already owns the equipment then this has been noted as sharing between partner organisations will help to reduce costs of the overall monitoring program.

Parameter / equipment	Use	Supplier	Est Cost (£)
Inorganic water samples	Characterization of water types and N and P in groundwater and surface water/ Ensure the lowest detection limits (or LOD) for N and P are used.	EA / NRW	~£50 per sample
Field water quality parameters	Collection of pH, DO, EC, temperature and redox in the field.	YSI / In situ	Loan from EA/NRW/BGS
Pump	Portable groundwater pump to collect water samples from dipwells and boreholes	WASP	Loan from EA/NRW/BGS
Rainwater quality	Characterization of rain water quality		~£50 per sample
Nitrogen and Oxygen stable Isotopes	Source attribution of nitrogen using 15N/14N + 18O/16O isotopes in groundwater and surface water.	BGS	£30-44 per sample (UEA) £140 per sample (NERC Labs)
CFC and SF_6	Age dating of young waters	BGS	£230 per sample
Diffusion tubes	Collection and analysis of atmospheric deposition data	Enviro Technologies/Gradko (NO2), CEH Edinburgh (NH3 badge samplers)	NO2 tube and analysis £7.90 (needed in quadruplicate per month per site) NH3 badge sampler and analysis £25 (needed in triplicate per month per site)
Dipwell casing	Installation of new monitoring points to sample groundwater	MGS Geotechnical	<£200
Groundwater levels	Characterization of groundwater levels using a vented or non vented pressure transducer	Solinst/Diver/Hobo/	Loan from EA/NRW/BGS
Surface water gauges and flow	Estimation of flow into or out of a wetland from any surface water feature .e.g ditch, spring or stream, using manual flow meter or automated data logger	BGS	Loan from EA/NRW/BGS
Survey equipment	Accurate survey of location and elevation of all monitoring equipment. Using Leica Smartrover	BGS	Loan from BGS

11.5 RISKS

The following risks are considered for any future work, namely onsite investigations and source apportionment work, following on from recommendations made within this report:

- **Project Management:** a project group should be assembled early on to review and comment on proposals and to select and agree upon the sites for the future study. A single project manager should take charge of the project.

- **Unrepresentative site selection:** It will be important to consider the types, locations and pressures of any sites included in future work.

- **Inconclusive results:** It is highly possible that even after collecting data sets at various sites that the results are ambiguous or inconclusive (see Chapter 12).

- **Funding:** funding or time in kind should be sort from all partners including, but not limited to Environment Agency, Natural Resources Wales, Natural England, British Geological Survey (NERC) and the Center for Ecology and Hydrology (NERC).

12. Research Needs

12.1 ECOLOGICAL

The site level assessment of nitrogen deposition impacts present a range of difficulties. Emmett et al. (2011) list the following shortfalls in understanding;

- Time scale of responses to background N deposition in the UK are poorly documented
- Long term monitoring is available only from very few locations
- Historic data for vegetation composition, plant and soil chemistry are rare thus we do not know how many habitats have changed already
- It is very difficult to separate the effects of other sources of nutrient input (e.g agricultural run off, site management) from atmospheric deposition

In addition (Bobbink & Hettelingh 2011):

- The combined nitrogen load from groundwater and atmospheric sources may exceed biological thresholds even where separately the critical load or GWDTE threshold are not exceeded.

Emmet et al. (2011) also suggest that Common Standards Monitoring is not suitable to detect N deposition impacts on individual sites due to the lack of repeat monitoring at permanent quadrats over time meaning changes in vegetation are not likely to be recorded. Stevens et al. (2009) make suggestions for how the assessment of atmospheric deposition and critical loads can be taken into account during SSSI condition assessments.

Adams (2003) lists the following research needs relating to atmospheric nitrogen deposition:

- improved understanding and quantification of the N cycle, particularly relatively unstudied processes such as dry deposition, N fixation and decomposition/rnineralisation;
- carbon cycling as affected by increased N deposition;

12.2 CRITICAL LOADS

Critical loads do not exist for all habitat types in the UK and the digital maps of interest feature locations and areas are not currently available. Thus to improve the use and application of critical loads;

- Further data and evidence of nitrogen impacts on sensitive habitats is needed to enable new critical loads to be derived and current values to be improved (Bobbink & Hettelingh, 2011).
- Spatial digital data on the location of and areas occupied by designated feature habitats (e.g. NVC mapping) within designated sites needs to be improved to enable the area of sensitive habitats at risk from atmospheric deposition to be better quantified.
- Critical loads do not currently take account of inputs of N from non-atmospheric sources, although this knowledge gap is noted (Bobbink & Hettelingh 2011), there are currently no recommendations on how to address this.

12.3 SOURCE APPORTIONMENT AND NITROGEN BUDGETS

Quantifying a nitrogen budget for a GWDTE will require information on the sources, pathways and receptors for nitrogen from both atmospheric and terrestrial sources. Furthermore the fate of nitrogen within the GWDTE in terms of retention, fixation, attenuation, accumulation of N in peat, uptake by plants and loss via processes such as denitrification needs to be better understood (e.g. Drewer et al. 2010). Recharge mechanisms and bypass flow mechanisms, for example in karst terrains, should also be considered as these may offer direct pathways to groundwater bypassing the soil and unsaturated zones where attenuation of nitrogen could take place. Härdtle et al. (2009) also show that management schemes (grazing and mowing), in conjunction with atmospheric deposition, can have effects upon the N and P budgets of Heathland Ecosystems. **Very few studies have assessed impacts from atmospheric and surface or groundwater inputs at the same site. This is a major knowledge gap.**

Source apportionment studies would need to distinguish between atmospheric and terrestrial sources of nitrogen perhaps using nitrogen and oxygen stable isotopes (e.g. Saccon et al. 2013) and each site would require a preexisting hydrogeological conceptual model. It should be noted that by the term 'source apportionment' we are hoping to define the relative sources of pollution e.g. agriculture 60% road traffic 40 % and we are NOT trying to identify specific locations, e.g. Mr Smiths Farm. Existing source apportionment tools such as the Environment Agency N&P spreadsheet calculator (AMEC, 2010) could benefit catchment wide source apportionment studies, it has been applied in recent studies in the Linconshire Chalk (AMEC, 2012).

Recommendations from EEA (2005) are applicable to such studies and include the need for:

- Data to quantify annual discharges from point sources (e.g sewage systems)
- Data to quantify annual retention within the wider hydrological cycle
- Information on groundwater residence time and degradation of nitrogen within aquifers
- Information on agricultural practices to allow development of models for nutrient loss

13. Conclusions

Many groundwater dependent terrestrial ecosystems (GWDTEs) in England and Wales are under pressure from nutrient enrichment, from both terrestrial (surface water – groundwater) and atmospheric sources. The Water Framework Directive classification has highlighted that there are up to **65 groundwater bodies in England and Wales at risk** due to chemical (nutrient) pressures at a groundwater dependent terrestrial ecosystem (GWDTE). Groundwater however is just one pathway for nutrients. The need to better understand all of the sources and pathways for nutrients is essential to inform WFD programs of measures aimed at reducing nutrients at GWDTEs.

A critical review of available literature highlighted the following knowledge gaps:

- There are very few studies (N budgets) that consider both inputs from the hydrological cycle and the atmosphere in sufficient detail
- There are 35 GWDTEs that have current or historic information relating to on site atmospheric deposition
- Over half of the atmospheric monitoring sites are within 10km of a designated GWDTE and could provide information for future work

GIS study combining results of Critical Loads and Threshold Values

This study represents the first attempt to combine atmospheric nitrogen deposition loads (Critical Loads), terrestrial groundwater nitrate (Threshold Values) and condition assessments for all 3320 GWDTEs included within the Water Framework Directive classification process.

In England and Wales:

- ~64 % (2129sites) exceed the nitrogen critical load for at least one feature habitat
- ~3 % (107sites) exceed their groundwater Threshold Value for nitrate as N mg/l
- ~3 % (87sites) exceed both their Critical Load and Threshold Value

The lower number of sites exceeding their threshold value compared to critical load is not representative of the true risks or potential pressures from groundwater mediated nitrate. The low percentage of sites exceeding their TV (3%) is a reflection of the lack of nutrient data from WFD monitoring considered to by hydrologically linked to a GWDTE. In addition localised pressures such as nutrient rich surface runoff from fields adjacent to GWDTE may be significant contributors to nitrate loading.

Implications of these results for the WFD classification

- There is a need for the collection of more water quality data at / or in WFD monitoring points considered to be hydrologically linked to GWDTEs, to provide data for the future classification of GWDTEs against groundwater threshold values.

- The Critical Load information should be included within future WFD classification so that assessments consider atmospheric loading in conjunction with terrestrial loading

- It is possible that many GWDTEs are in poor condition primarily due to atmospheric deposition, however a greater understanding of the levels of terrestrial nutrients, acidification, source and fate of nutrients in wetlands is needed before any such assessment can be undertaken

Implications of these results for effective catchment management

- The results clearly show that the majority of sites (64%) exceed their critical load, suggesting that effective catchment management and the regulation of emissions from industry and agriculture need to be considered together to help GWDTEs achieve favourable status.
- It is possible to regulate point source emissions (e.g factories, poultry farms) however the contribution of diffuse, and perhaps unregulated, nitrogen to the loading at a GWDTE may be very difficult, if not impossible to regulate.
- There still exists much uncertainty about the relative contribution and fate of terrestrial and atmospheric nutrient loading at GWDTEs, and with this uncertainty a reduced ability to successfully mitigate against these pressures.
- Where localised nutrient enriched waters, e.g. agricultural surface runoff, are known to have significant impacts along the periphery of GWDTEs they may be controlled by local land management agreements. This localised management may offer substantial improvements to the GWDTE and be both cost and time effective.
- There is a need to define a defensible methodology to quantify nitrogen loading (source apportionment) both at GWDTEs and potentially within entire groundwater bodies. Defining the sources and pathways for nutrients will allow targeted and effective WFD programs of measures to be undertaken.

Future source apportionment studies: partnerships, risks and costs

It is hoped that future work will address source apportionment studies at a subset of preselected GWDTEs in England and Wales, that could be selected from site listed in Table 8. Utilising sites with existing groundwater monitoring networks, vegetation mapping and conceptual models we will use traditional (i.e water chemistry and vegetation mapping) and novel techniques (stable isotope and groundwater age dating) to better understand the source apportionment of nutrients.

A project board consisting of partners from EA, NE, NRW, CEH and BGS, with expertise in air quality, hydrogeology and wetland ecology should be formed. Risk to any potential source apportionment project can be reduced with effective planning, but could include: unrepresentative selection of GWDTEs, poor project management, inconclusive results or failure to secure sufficient funding and ‘buy in’ from partner organisations.

Possible research hypothesis, sources of existing data, costs of analysis and equipment are detailed within the report as are opportunities to share equipment and services with partners thus reducing the cost of the project.

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Glossary

BGS	British Geological Survey (NERC)
CEH	Centre for Ecology and Hydrology (NERC)
CBED	Concentration Based Estimated Deposition (See RoTAP, 2012)
CCW	Countryside Council for Wales (now part of Natural Resources Wales)
CLRTAP	Convention on Long Range Transboundary Air Pollution
CSM	Common standards monitoring
EA	Environment Agency: lead environmental regulator in England
FRAME	Fine Resolution Atmospheric Multi-pollutant Exchange, model is a Lagrangian atmospheric transport model used to assess the long-term annual mean deposition of reduced and oxidised nitrogen and sulphur over the United Kingdom.
GWB	Groundwater body: essentially a reporting unit for the Water Framework Directive
GWDTE	Groundwater Dependent Terrestrial Ecosystem
HD	HabitatsDirective
NE	Natural England: lead conservation agency in England
NECD	National Emissions Ceiling Directive
NNR	National Nature Reserve
NRW	Natural Resources Wales: environmental regulator for Wales replaced Environment Agency Wales, Countryside Council for Wales and Forestry Commission Wales on 1st April 2013.
NERC	Natural Environment Research Council
SAC	Special Area of Conservation
SSSI	Site of Special Scientific Interest
UKTAG	UKTAG is a partnership of the UK environment and conservation agencies which was set up by the UK wide WFD policy group consisting of UK government administrations. It was created to provide coordinated advice on the science and technical aspects of the European Union's Water Framework Directive (2000/60/EC).
WFD	Water Framework Directive (2000/60/EC).

Appendix 1

Name	Organisation	Role or interest
Project Team		
Natalie Phillips (Kieboom)	Environment Agency	Project manager and Geosciecne
Dr Mark Whiteman	Environment Agency	Modelling Specialist
Gareth Farr	British Geological Survey	Hydrogeologist
Jane Hall	Center for Ecology and Hydrology	Critical Loads
Consultees and partners		
Dr Rob Kinnersley	Environment Agency	Air Quality
Ann Skinner	Environment Agency	Senior Conservation Advisor
Mella O'Driscoll	Environment Agency	Air quality
Sarah Watkins	Environment Agency	Air quality
Paul Howeltt	Environment Agency	Groundwater
Iain Diack	Natural England	Senior Specialist - Wetlands
Anna Wetherell	Natural England	Hydrogeologist
Gorden Wyatt	Natural England	Senior Specialist, Air Quality
Dr Peter S Jones	Natural Resources Wales	Terrrestrial ecosystems group
Rachel Breen	Natural Resources Wales	Geoscience Team
Khalid Aazem	Natural Resources Wales	Air quality
Debbie Allen	British Geological Survey	Hydrogeologist
Laurence Jones	Center for Ecology and Hydrology	Dune habitats, Nitrogen impacts research
Camilla Keane	PLINK network	

Appendix 2

GWDTE SSSI name	Country	EU_DES	CONDITION	WFD Threshold Value exceeded	Maximum excedance (AAE) of nutrient nitrogen critical loads based on site area-weighted deposition kg
MIDDLE HARLING FEN	England	Non EU	Unfavourable recovering	YES	55.17
MOSS CARR	England	Non EU	Unfavourable recovering	YES	35.98
DECOY CARR, ACLE	England	EU	Unfavourable recovering	YES	35.85
BARLE VALLEY	England	EU	Unfavourable recovering	YES	32.56
ABBOTS MOSS	England	EU	Unfavourable recovering	YES	30.46
RINGDOWN	England	Non EU	Unfavourable recovering	YES	29.81
EAST HARLING COMMON	England	Non EU	Unfavourable recovering	YES	29.62
HOLT LOWES	England	EU	Unfavourable recovering	YES	29.44
SHORTHEATH COMMON	England	EU	Unfavourable recovering	YES	29.37
BASINGSTOKE CANAL	England	Non EU	Unfavourable recovering	YES	27.66
MARAZION MARSH	England	EU	Unfavourable recovering	YES	26.99
DERSINGHAM BOG	England	EU	Unfavourable recovering	YES	26.51
BONEMILLS HOLLOW	England	Non EU	Unfavourable recovering	YES	25.98
NODDLE END	England	Non EU	Unfavourable recovering	YES	25.73
NORTH DARTMOOR	England	EU	Unfavourable no change	YES	25.26
RUTTERSLEIGH	England	Non EU	Unfavourable no change	YES	24.16
HURCOTT & PODMORE POOLS	England	Non EU	Unfavourable no change	YES	23.68
DANES MOSS	England	No data	Unfavourable no change	YES	23.63
THURSLEY, HANKLEY & FRENSHAM COMMONS	England	EU	Unfavourable no change	YES	23.46
TRING RESERVOIRS	England	Non EU	Unfavourable no change	YES	23.37
LOWER COOMBE & FERNE BROOK MEADOWS	England	Non EU	Unfavourable no change	YES	23.23
STOBOROUGH & CREECH HEATHS	England	EU	Unfavourable no change	YES	23.21
RIVER HULL HEADWATERS	England	Non EU	Unfavourable declining	YES	23.13
THE DARK PEAK	England	EU	Unfavourable declining	YES	21.46
EASTERN PEAK DISTRICT MOORS	England	EU	Unfavourable declining	YES	21.22
RIVER WENSUM	England	EU	Unfavourable declining	YES	21.09
BRASSEY RESERVE & WINDRUSH VALLEY	England	Non EU	Unfavourable declining	YES	20.55
TOLLER PORCORUM	England	EU	Unfavourable declining	YES	20.16
SHACKLEWELL HOLLOW	England	Non EU	Unfavourable declining	YES	19.40
RIVER CAMEL VALLEY & TRIBUTARIES	England	EU	Unfavourable declining	YES	19.36
LOWER WOODFORD WATER MEADOWS	England	EU	Unfavourable declining	YES	19.25
EAST ASTON COMMON	England	Non EU	Unfavourable declining	YES	18.85
BRANSBURY COMMON	England	Non EU	Unfavourable declining	YES	18.82
GREYWELL FEN	England	Non EU	Unfavourable declining	YES	18.66
STOWELL MEADOW	England	Non EU	Unfavourable declining	YES	18.10
RIVER AVON SYSTEM	England	EU	Unfavourable declining	YES	17.72
GELTSDALE & GLENDUE FELLS	England	EU	Unfavourable declining	YES	17.55
SANDWICH BAY TO HACKLINGE MARSHES	England	EU	Unfavourable declining	YES	16.82
CUMWHITTON MOSS	England	Non EU	Unfavourable declining	YES	16.73
MOORS RIVER SYSTEM	England	Non EU	Unfavourable declining	YES	16.50

GWDTE SSSI name	Country	EU_DES	CONDITION	WFD Threshold Value exceeded	Maximum excedance (AAE) of nutrient nitrogen critical loads based on site area-weighted deposition kg
AVON VALLEY (BICKTON-CHRISTCHURCH)	England	Non EU	Unfavourable declining	YES	16.14
PETTYPOOL BROOK VALLEY	England	Non EU	Unfavourable declining	YES	15.97
MOORTHWAITE MOSS	England	Non EU	Unfavourable declining	YES	15.76
DUCAN'S MARSH, CLAXTON	England	EU	Unfavourable declining	YES	15.73
TROUTSDALE & ROSEKIRK DALE FENS	England	Non EU	Unfavourable declining	YES	15.28
LYTHAM ST ANNES DUNES	England	Non EU	Unfavourable declining	YES	13.51
LANGFORD MEADOW	England	Non EU	Unfavourable declining	YES	13.38
RIVER TEST	England	Non EU	Part destroyed	YES	13.10
LLWYN	Wales	EU	No data	YES	12.44
ERYRI	Wales	EU	No data	YES	12.12
AFON TEIFI	Wales	EU	No data	YES	11.74
BLAEN NEDD	Wales	EU	No data	YES	9.02
CLEDDON BOG	Wales	Non EU	No data	YES	8.80
MYNYDD PRESELI	Wales	EU	No data	YES	8.10
CWM DOETHIE - MYNYDD MALLAEN	Wales	EU	No data	YES	8.03
BRYN-BWCH	Wales	EU	No data	YES	7.93
STACKPOLE	Wales	EU	No data	YES	7.82
OXWICH BAY	Wales	EU	No data	YES	7.06
GWEUNYDD DYFFRYN NEDD	Wales	EU	No data	YES	6.80
CORS GOCH	Wales	EU	No data	YES	6.42
MERTHYR MAWR	Wales	EU	No data	YES	6.29
SOUTH EXMOOR	England	Non EU	Favourable	YES	5.82
FOWLMERE WATERCRESS BEDS	England	Non EU	Favourable	YES	5.68
WYRE FOREST	England	Non EU	Favourable	YES	5.59
NEWBOURN SPRINGS	England	Non EU	Favourable	YES	5.43
RIVER EDEN & TRIBUTARIES	England	EU	Favourable	YES	4.53
CORFE & BARROW HILLS	England	EU	Favourable	YES	4.46
EAST WALTON & ADCOCK'S COMMON	England	EU	Favourable	YES	4.38
CORFE COMMON	England	EU	Favourable	YES	4.18

Appendix 2: List of GWDTEs that exceed both their Critical Load and fail their Water Framework Directive Threshold Values