Nitrogen transport and transformation at the groundwater – surface water interface – How important is the Hyporheic Zone?

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In riparian floodplains, groundwater and surface water are often well connected. Especially during base flow conditions, groundwater contributions to the river represent a major proportion of the discharge. Increasing nitrate concentrations in many groundwater aquifers (the nitrate time bomb) and the alarming prognosis of critically high groundwater nutrient contributions to surface waters, make it essential to understand the implications of transport and transformation processes at the direct interface between groundwater and surface water. Especially the hyporheic zone, the area where groundwater and surface water are mixing in the streambed, is been considered to substantially contribute to the amelioration of groundwater nitrate contributions and the preservation of the stream ecological health.

At the River Leith in Cumbria investigations have been carried out, aiming to quantify groundwater surface water exchange fluxes, nitrate transport and transformation rates in the hyporheic zone. The investigations at the Leith showed significant changes of nitrate concentrations in the upwelling groundwater, which have been found to be dependent on (i) streambed physical conditions controlling fluxes, mixing and residence times and on (ii) chemical factors as the pore water dissolved oxygen content and redox conditions. For the investigated stream sections, heterogeneous patterns of groundwater accretion rates and spatially variable groundwater – surface water mixing in the streambed have been observed to cause a high spatial variability of the pore water nitrate concentrations. Nitrate retention hotspots have been identified in direct neighbourhood to nitrate enrichment and nitrification areas, depending on the streambed redox conditions. The high observed turnover rates, but also the significant spatial heterogeneity of nitrate attenuation and enrichment, even in the relatively small-scale research area, are far more complex then acknowledged so far and demand for a more detailed investigation of hyporheic controls on nitrate transformation. The observations at the Leith also highlight the fact that the streambed area that shows substantial nitrate concentration changes in the upwelling groundwater may exceed the classical understanding of the hyporheic zones spatial extent.

According to the current understanding of the hyporheic zones extend this is delineated by the mixing of groundwater and surface water. However, the investigations at the River Leith show that significant nitrate transformation may occur even in areas where groundwater; surface water mixing occurs only on an episodic basis. Our results furthermore indicate that the impact, nitrate contributions from the upwelling groundwater are causing for the surface water concentrations, varies in time. Future assessments of groundwater nitrate contributions and of the hyporheic retention efficiency may need to consider the temporally variable significance of this impact on the in-stream ecological processes.

The shallow biogeochemically active hyporheic zone: nitrate sink but a methane source.

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In permeable catchments, nitrate (and other contaminants) resident in the ground water are transported via subsurface flowpaths, but their ultimate fate may depend upon contact with the biogeochemically active hyporheic zone (HZ) of the river bed sediments. The capacity of the HZ to remove nitrate may modify the availability of N for the river biota and has important implications for the management of impacted systems (WFD and EU Nitrates Directive). However, the functional significance of the HZ will depend on its reactivity (processing rates) and spatial extent, both of which are not well described for chalk rivers.

Although the high permeability of the alluvial sediments may permit hydrological exchanges over significant spatial scales, our data suggest that the HZ of some chalk streams is very thin. In addition, over spring and summer there can be a marked increase in the silt/clay fraction of the HZ, a concomitant drop in mean particle size and, hence, inferred permeability. Such areas tend to be transient and are often associated with deposition beneath macrophyte stands (*Ranunculus*).

While these conditions favour the reduction and attenuation of nitrate they create ideal conditions for methanogenesis. Spring and summer is associated with an increase in methane transport through *Ranunculus* stems and an increase in water column methane concentration. Methane production and efflux can be similar to that from some UK peatlands and could be coupled to a transient input of organic matter, possibly of terrestrial origin.

The dispersal and deposition of plant propagules in groundwater-fed rivers: linking hydrology and ecology

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Research has shown that rivers are an important agent for transporting and depositing plant propagules, but the relationship between the hydrological regime and riverbank vegetation is not well understood. This paper presents the findings from studies conducted along two UK groundwater-fed rivers, the River Tern, Shropshire and the River Frome, Dorset, which explored propagule transport and deposition in the river channel and on the riverbank.

Sediment and propagules were sampled from the river bed and at varying elevations on the riverbank at all three sites. In addition, propagule transport in the river channel and from aerial seed fall was investigated along the River Frome. The abundance and diversity of propagules were considered in relation to the river water levels and sediment deposition. The species found in the samples were also compared to the standing vegetation and the seed bank, to identify 'new' species.

Analysis revealed that aerial seed fall generated few propagules of low diversity and the river introduced large numbers of propagules and new species, resulting in high rates of propagule deposition on the riverbank. In all reaches, the abundance and diversity of deposited propagules changed with season and position on the riverbank, with very high numbers of propagules deposited in the winter months, following high flows. Winter deposits were characterised by high species richness, with many 'new' species recorded. Strong relationships were identified between the abundance and diversity of deposited propagules and river water levels and associated sediment deposition. Winter flows were very important for remobilising propagules from the river bed, introducing new species to the sites and for transporting propagules from the channel into the riparian zone. These findings show that in groundwater-fed river systems such as the Frome and Tern, high flows are very important for maintaining connectivity and promoting floristic diversity in the riparian zone.

A study of the hypogean fauna in England and Wales

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Groundwater ecology has received very little attention in the UK, however the preamble to the new EU Groundwater Directive encourages further research on groundwater ecosystem function and protection, and the well shrimp *Niphargus glenniei*, has recently been added to the UK Biodiversity Action Plan priority species list. This paper presents the results of a review of the distribution and ecological functions of subterranean aquatic fauna in England and Wales.

Over 500 records of stygobites (invertebrates that live solely in subsurface aquatic habitats) were found for groundwater and hyporheic systems, which were obtained primarily from the Biological Records Centre, the Environment Agency's BIOSYS, caving records, published works and personal communications. In contrast to Europe (particularly karstic regions of France and the Balkans) there are very few stygobites recorded in England and Wales. They are typically found where the bedrock geology is fractured and calcareous, and usually in areas to the south of the maximal extent of the Pleistocene glaciation. Stygobites are slow moving and slow to disperse. Some species have been recorded from only one or two sites and it appears that they have not yet recolonised habitats affected by glaciation. Research suggests that stygobites are particularly vulnerable to anthropogenic disturbance due to their restricted distributions, poor dispersal, low reproductive rates and poor competitive ability.

Although species richness of stygobites is limited, the hyporheic and groundwater habitats make a unique contribution to UK biodiversity. There are also extensive assemblages of stygophile fauna occurring in both hyporheic and groundwater habitats; these may perform important functions such as modulating the activity of the hyporheic biofilm by grazing and bioturbation.

The paper will consider what ecological functions and services the hypogean fauna provide, and outline options for their protection and enhancement, which are likely to be a part of the European Commission's review of the GW Directive in 2013.

The response of aquatic invertebrates to hydrological extremes in riverine epikarst

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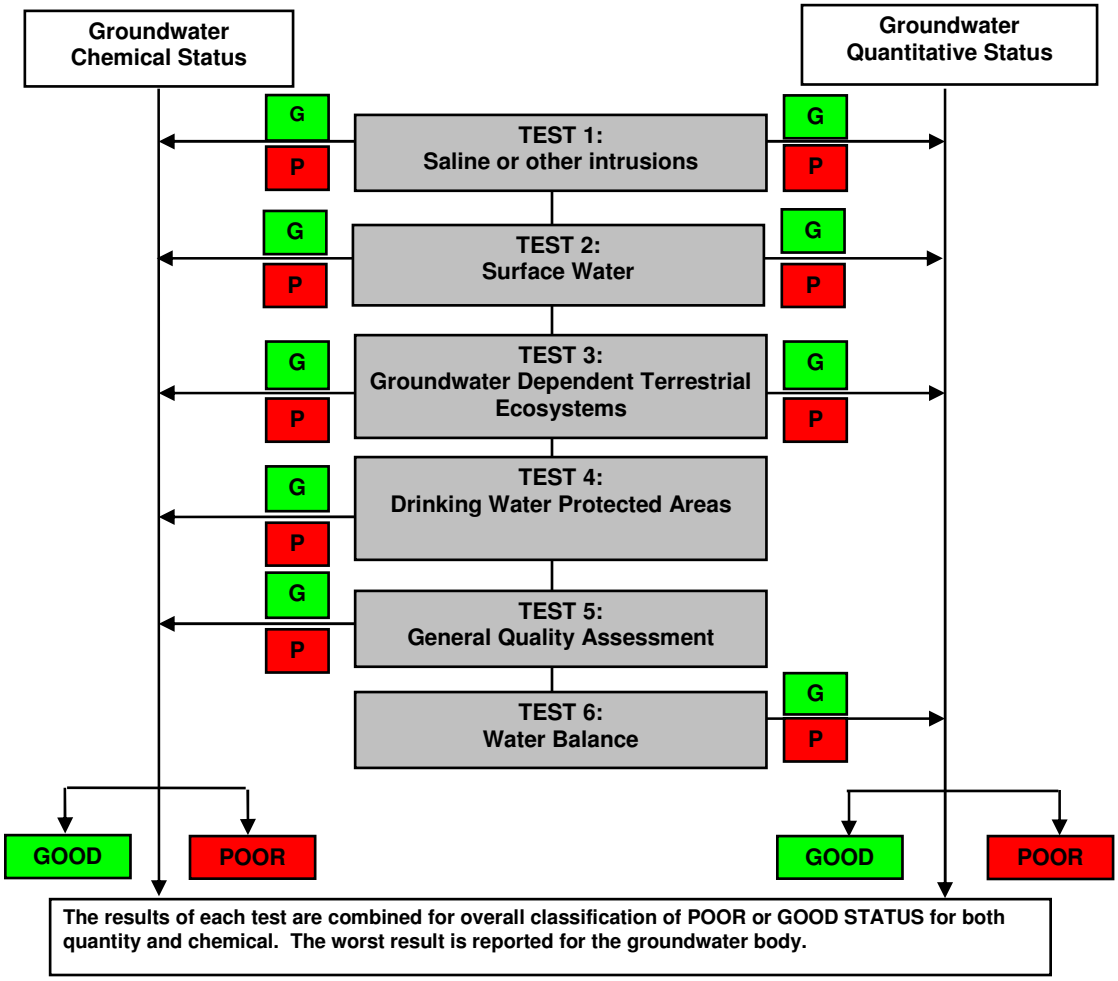
Epikarstic habitats may be subject to extreme hydrological variability, but the ecology of such habitats has received little attention in the UK. The summer floods of 2007 provided a unique opportunity to examine how the aquatic invertebrate fauna in the naturally ephemeral epikarstic headwaters of the River Lathkill (Derbyshire) responded to rapid wetting and subsequent drying. At perennial sites, the initial flood disturbance resulted in low invertebrate abundance and species diversity, followed by a gradual recovery as flow declined. At ephemeral sites, the sudden inundation associated with the floods facilitated the rapid colonisation of the river by a limited number of taxa (particularly *Gammarus pulex*), probably from hypogean refugia including the epikarst and caves. The abundance of all colonising taxa at these ephemeral sites remained low as flow declined and the streambed ultimately became dry. The survival of aquatic invertebrates following streambed drying was investigated, and was found to be restricted to a relatively small number of taxa. Of these, some, for example *Gammarus pulex*, only persisted for a few days in areas retaining some moisture. Others, including a copepod (Cyclopoida: *Diacyclops bicuspidatus*), larval chironomids (including *Metriocnemus* sp., *Bryophaenocladius* sp. and *Rheocricotopus fuscipes*), and adult Coleoptera (*Agabus guttatus*) were found alive in field damp sediments more than a months after flow ceased. Rehydration of dry sediments in the laboratory demonstrated the survival of other taxa, including cased caddisflies of the genus *Stenophylax* and stoneflies from the family Nemouridae, indicating that these taxa must possess desiccation resistant life stages. These results suggest that refugial habitats (which retain free water) and desiccation resistant life stages (eggs, larvae and adults) both play a role in the survival of invertebrate fauna in the ephemeral streams of temperate climates, as occurs in arid and semi-arid regions.

WFD Groundwater body status classification: it's the ecology, stupid!

Tim Besien

Environment Agency

We need to assess groundwater body status to comply with the Water Framework Directive, the Groundwater Direction and the Groundwater Daughter Directive. We must assess both chemical and quantitative status separately for each groundwater body. Chemical and quantitative status can be either good or poor. This presentation briefly describes each of the five tests for chemical status classification and each of the four tests for quantitative status classification (see figure below). The presentation goes on to explain the central role that ecology takes in the Surface Water, Wetland and Water Balance tests. Initial draft results for the individual tests are presented, along with the overall results for groundwater body chemical and quantitative status.



Significant damage to Groundwater-dependent Terrestrial Ecosystems: Good regulation or lack of information?

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Recently, the Environment Agency, working with partners in Natural England and the Countryside Council for Wales, has classified each groundwater body in England and Wales at either good or poor status according to whether groundwater-dependent terrestrial ecosystems (GWDTEs) are significantly damaged. The work has been undertaken as part of groundwater status assessments for the EU Water Framework Directive (WFD).

Firstly, a risk screening exercise was undertaken (Hulme et al, 2007). This followed a methodology based on the source-pathway-receptor concept, where the source of pressure is the abstraction, or source of groundwater pollution, the pathway is the transmission route from the aquifer to the receptor, which is the groundwater-dependent wetland ecosystem. The results from the national screening were checked against local expert knowledge at 10 workshops throughout England and Wales and revised accordingly. The outputs were maps showing which wetlands are at risk of damage due to poor groundwater quality or inadequate quantity. Of 1,368 sites assessed, 63 were considered at high risk from abstraction pressures, and 117 at high risk from groundwater chemical pressures.

Secondly, a site-specific assessment was made, for those high-risk sites where condition data from the conservation agencies indicated that unfavourable condition could be due to reasons related to abstraction or chemical pressures acting through the groundwater body. A seven-step process was followed, as defined by the UK Technical Advisory Group for the WFD. This involved defining a site-specific threshold for chemical pressures, and estimating the degree of departure from required environmental supporting conditions (e.g. flows and levels), as defined in the Environment Agency's Eco-hydrological Guidelines for Lowland Wetland Plant Communities (Wheeler et al, 2004) and similar documents produced by Natural England for other habitat types.

71 groundwater bodies were considered to be at good status, high confidence, with respect to quantitative pressures, however, 229 groundwater bodies were at good status, low confidence. 58 groundwater bodies were at good status, high confidence with respect to chemical pressures, and 245 were at good status, low confidence. This highlights the uncertainty due to lack of data, especially chemical monitoring and ecological survey data, from wetland sites. Five groundwater bodies were at poor status due to actual ecological damage caused by quantitative pressures, and 2 due to chemical pressures.

Further work is required to increase confidence in the risk assessment methodology, to establish efficient and effective investigation techniques for determining significant damage (particularly due to chemical pressures), and to refine and extend our knowledge for the eco-hydrological requirements of wetland conservation interest features.

Flow accretion profiling as a method of hydrological characterisation of wetlands in permeable catchments

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Hydro-ecological studies of wetlands have historically been very site-specific, in order to gain any certainty about the water sources contributing to and hydrological processes that control floral and fauna communities. This often requires installation of monitoring networks, and hence significant time and effort. Where characterisation of a large number of wetlands is required, there is a need for alternative approaches that operate at a broader scale.

Flow accretion profiling along rivers is a recognised method for improving the understanding of catchment hydrogeological processes. Flows are measured at a number of points along the river to establish "gaining" and "losing" reaches. This allows the areas where the river is interacting with groundwater to be established, and gives a good spatially-distributed understanding of the surface-groundwater interactions.

Our study of floodplain wetlands along the River Lambourn illustrates that flow accretion profiling can also be valuable for wetland characterisation at a catchment scale. We carried out within-wetland studies of individual sites to establish the hydrological processes occurring at those locations. In conjunction with this, flows were measured at regular intervals along the river to develop profiles of the flow accretion. We found that wetland areas adjacent to gaining river reaches had the greatest interaction with groundwater. In contrast, wetlands adjacent to reaches with little accretion were found to have relatively little direct groundwater contribution, instead being reliant on contributions from the river and near-surface deposits. Although more intensive monitoring is necessary to establish a detailed hydrological understanding of individual wetland sites, examining flow accretion profiles in the adjacent river can provide a useful first step or screening exercise in wetland characterisation.

The wetland water balance: Linking hydrogeological processes to ecological effects

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This paper describes a modelling methodology for linking hydrological and hydrogeological process to ecological effects using the wetland water balance approach. In recent years the methodology has been applied to sites including ecologically sensitive lakes, Special Protection Area (SPA) wetlands and large floodplain wet grasslands in connection with the Habitats Directive and Water Level Management Plans, amongst other policy drivers. A case study on the Arun Valley SPA will be presented. The modelling methodology links regional scale hydrogeology to wetland hydrology that is typically influenced by local processes occurring at a reduced spatial scale (eg. management). To assess impacts, it is therefore necessary to understand not only the hydrological sources of water that are affected by abstraction, but also to consider how the magnitude of these processes relates to other processes influencing wetland water levels. To apply the wetland water balance model daily time series are calculated for the main inputs and outputs to the wetland. Topographic data are then used to translate changes in water volume to changes in water level and the open area of water. By developing a model capable of predicting wetland water levels, the suitability of conditions for ecological habitats or species can be assessed with reference to national guidance material on hydro-ecological relationships. Once calibrated, the model can be extended over longer time periods and perturbed by alternative management options (eg sluice control), and groundwater or surface water abstraction scenarios to assess impact. Since the approach links changes in water volume to ecology, the options and measures that are most relevant at the ecological scale can be compared and assessed. The case study was part of Southern Water's PRO4 Environment Programme. The approach has considerable potential for a wide range of wetland applications including the Water Framework Directive programmes of measures.

Balancing hydro-ecological needs with sustainable groundwater abstraction: Anglian region's framework for managing groundwater resources.

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Anglian Region has the largest number of wetlands designated under the EU Habitats Directive. It is also an area that relies heavily of groundwater abstraction for Public water supply and for spray irrigation. Consequently there are hundreds of ground (and surface) water licences abstracting in close proximity to designated wetland sites.

In 1999 a strategy was implemented to develop groundwater models for all aquifer units across the Region and designed to provide the Agency with the tools and information to make groundwater resource decisions based on sound science and good technical practice. There are two strands to the work:

1. Development of distributed groundwater flow models

Eight regional distributed groundwater models, covering the main aquifers have, or are being, constructed. These underpin the analyses undertaken for the vast majority of the Habitat sites within Region.

2. RSA and Habitats Directive Review of Consents

Hydro-ecological site characterisation was undertaken for around 90 wetlands, including fens, bogs, floodplain and coastal grazing marsh, open water (rivers, broads, clay pits and ponds), estuaries and coastal sites. These described the hydro-ecological functioning of the sites and presented a risk assessment for the effects of abstraction, based on simple analytical techniques. As part of this site characterisation process site works were proposed with the specific aim of obtaining data that clearly links the location of the important ecological features with shallow and deeper water tables. Additionally guidance was produced on linking Hydrological Impact to Ecological Effect.

Hydrological Impact Assessments informing the Stage 3 Appropriate Assessments were underpinned by the development of target hydrological regimes, based on the Hydro-ecological guidelines (Wheeler et al, 2004) and similar documents, and outputs from the regional models. It was possible to conclude that 'no adverse effect on the integrity of sites had been proven' for a number of sites. However those remaining have progressed to Stage 4 and are subject to on-going work.

Does 10 cm matter? – Significance of groundwater table change to GWDTE

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Regional integrated surface water and groundwater models are used extensively by the Environment Agency (EA) to assess both natural and anthropogenic influences on the water environment. The models represent complex groundwater systems and their interaction with the surface environment. However, there are limitations, particularly related to scale and to the assessment of impact on groundwater dependent terrestrial ecosystems (GWDTE).

The resolution of regional model networks is generally 200 or 250 m^2. Within model cells there is uniformity of properties and is thus no variation in topography, groundwater table elevation or soil properties. GWDTE can be small in size with often subtle variation in topography and soil characteristics. This results in a shallow groundwater table environment that is spatially variable and to which specific plant communities adapt. Influences such as groundwater abstraction or drought result in changes in the groundwater table, yet not evenly distributed within a GWDTE.

Regional models can simulate changes in groundwater levels. However, such changes need to be considered in the context of water needs of plant communities. It is here that groundwater modellers struggle. Firstly the models represent saturated groundwater systems, while plants in GWDTE require specific soil moisture conditions. Therefore does a 10 cm decline in the groundwater table matter?

Recent work has seen the introduction of soil moisture simulation approaches. This is a step forward towards understanding the impact on plant communities. Although scale could be addressed with detailed saturated/unsaturated flow models, this can be time consuming and costly. And data are generally lacking at the GWDTE scale. We see the way forward through the development of practical tools that can be bolted on to regional models and that allow for representation of local scale within model cells. However, this cannot be achieved without the meeting of minds. Water specialists and terrestrial ecologists need to collaborate and work together in addressing the challenges that face the groundwater dependent ecological environment.

The eco-hydrology of wet dune slacks: experience from Winterton Dunes, Norfolk

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Wet dune slacks are distinctive wetlands that are sensitive to human influences on their hydrology. Dune slacks are characterised by seasonally fluctuating water tables; they may be waterlogged or have standing water in winter/spring but soils can dry out to a considerable depth in summer, depending on local hydrology. They must be considered as part of a larger dune system that functions as an eco-hydrological unit. Annex II and Red Data Book species are mainly associated with particularly sensitive early-successional stages that are base-rich and nutrient-poor.

Information on the hydrological conditions in a range of European dune-slack habitats in the Wadden Sea area, along the coasts of The Netherlands, Germany and Denmark, has been used to develop a new conceptual model for dune-slack hydrology, based on a water balance approach that accommodates the complexity of a sequence of hydrologically-connected slacks within a dune system (Davy *et al*. 2006). In Britain, field measurements and quantitative modelling studies are limited but recent moniroring at Winterton Dunes, a rare acid dune system on the east coast of Norfolk between Hemsby and Horsey and known for its small population of Natterjack Toad (*Bufo calamita*), has been used to test the generic conceptual hydrological model.

With the use of dip-wells and topographical data along two, 90-metre transects, water levels were monitored at Winterton NNR for 14 weeks during 2007 and showed that the current sea wall acts as a barrier to eastward flowing groundwater. The general groundwater flow direction is to the south-west, but with seasonal differences. During wet periods, precipitation is temporarily stored in the higher sandy dune areas, while the low-lying ponds overflow and groundwater infiltrates the fine- to coarse-sands and occasional gravel that comprise the dunes. During dry periods, water stored in the higher areas slowly drains until a balance is found as westward groundwater flow reaches the low-lying ponds where it is lost to evapotranspiration. Hydrochemical analysis of water samples collected along the transects and ponds confirmed a fresh (acid) water system with a slight seawater (sodium chloride) influence. Infiltration in the higher dune areas increases the mineral content of calcium and magnesium but, given the short period of monitoring during a mainly recharge period, no clear correlation with location or migration in groundwater was detected for iron. However, groundwater-fed springs show the visual effects of bacteria precipitating iron on the north-east side of the dune ponds.

Further research is required to determine the conservation measures necessary to restore sustainable habitats at Winterton and at other wet dune slacks in Britain if the situation in the Netherlands is to be avoided where experience suggests that dune slacks may be irreversibly sensitive to water abstraction, recharge variation and changes in water quality.

Reference:
Davy, A.J., Grootjans, A.P., Hiscock, K. & Petersen, J., 2006. *Development of eco-hydrological guidelines for dune habitats – Phase 1*. English Nature Research Reports, No. 696, 78 pp.

A hydrogeological study of Hatfield Moor Special Protection Area

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Hatfield Moor is the second largest area of lowland raised peat bog in England and is now undergoing a significant recovery programme following the cessation of peat stripping. Water management on the mire is critical to the ecology and Natural England have made major changes to the drainage system to reduce runoff. Yorkshire Water Services (YWS) holds two abstraction licences nearby and their impact is assessed under the Habitats Directive through a hydrogeological study which includes 3 years of intensive water level monitoring in nested piezometers. Conditions in the saturated and unsaturated zones in the peats and in lakes and ditches are investigated and are linked to those in the deeper drift and underlying Sherwood Sandstone. The density and quality of observations, and comparisons with the nearby Thorne Moors, have allowed the climatic impacts on the water regime to be disaggregated from those from the extended pump/recovery cycles. In view of the uncertainty in actual evapotranspiration from mires and bare peat, the methodology appears more robust than one relying extensively on modelling. The study has allowed the areas affected by abstraction and the types of impact to be identified. The work reveals some issues for the future management of the Moors given the likely impact of climate change.

Development of a high-resolution conceptual hydroecological understanding of an internationally recognised fen wetland – Cors Bodeilio, Anglesey, Wales

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The hydroecological functioning of wetland sites is usually understood only at a macro-scale through a knowledge of water sources and geological setting, and interpretation of the distribution of species and habitat types. Recent assessment of the impacts of various off-site influences on wetland hydroecology under the Habitats Regulations and the Water Framework Directive has highlighted the requirement for a more detailed conceptual understanding. In order to address this requirement at an example site, the Countryside Council for Wales and Environment Agency Wales have intensively investigated and instrumented Cors Bodeilio, an internationally recognised fen wetland which is part of the Anglesey Fens Special Area for Conservation (SAC).

Investigations at the site have included vegetation and surface water feature mapping, and lithological characterisation of wetland substrate through hand-auger survey and lightweight percussion drilling. Over twenty dipwells (up to 1.5 m deep) and two deeper (up to 7 m) piezometers have been installed to measure near-surface and deeper groundwater levels and quality. Water levels in these and in surface water features are monitored both manually and automatically at a high frequency. Two deep EAW observation boreholes are located within 2.5 km of the site, providing information on groundwater levels and quality in the underlying Carboniferous Limestone. Rainfall is monitored on-site using an automated raingauge.

The investigations have yielded information at high spatial, vertical and temporal resolutions, and this has been analysed and interpreted to produce a detailed conceptual hydroecological understanding of the site. Aspects of this site-specific understanding can be transferred to other sites, to help in the identification of key hydroecological processes and in turn lend greater confidence to hydroecological impact assessments.

The use of geostatistical mapping in the hydroecological assessment of abstraction pressures on the vegetation of three groundwater dependant terrestrial ecosystem sites of special scientific interest.

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Three project sites, classified as Sites of Special Scientific Interest, have been identified as groundwater dependent terrestrial ecosystems potentially affected by groundwater abstraction. One of the aims of the study was to provide an accurate assessment of the distribution and abundance of plants found on each site, as a baseline against which to measure any change over time. To establish whether any identified change is attributable to groundwater abstraction, the study developed a conceptual understanding of the groundwater supply mechanisms and the degree to which abstraction could potentially affect the availability of shallow groundwater to the water dependant vegetation of the sites.

Geostatistical Vegetation Monitoring uses GPS referenced survey methods to collect data that are free from the subjective assessment of vegetation boundaries by surveyors that has been a problem with traditional survey methods such as the National Vegetation Classification (NVC) system. Data collection is followed by geostatistical analysis using kriging methods, probability mapping and allocation of Ellenberg values to assess species soil moisture and pH requirements across each site.

Reproducible baseline species distribution maps for each site provide a platform for monitoring future long-term changes in vegetation composition. Variations in climatic conditions between subsequent years will lead to natural fluctuations in plant distributions. However, an assessment of the extent and direction of any change in species distribution, in conjunction with their relative needs for moisture and acid/basic conditions, should enable a determination to be made as to whether it is reduction in the amount of available calcareous groundwater that is responsible for any change to the ecology of the sites, or changes in other parameters, or possible ‘in combination’ effects.