ECOHYDROLOGICAL METHODS FOR THE INVESTIGATION OF SIGNIFICANT DAMAGE AT GROUNDWATER DEPENDENT TERRESTRIAL ECOSYSTEMS

G.Farr[1], M. Whiteman[2] & P.S.Jones[3]

[1]British Geological Survey
[2] Environment Agency
[3] Natural Resources Wales
garethf@bgs.ac.uk

ABSTRACT

This paper aims to share the experiences of UK conservation and environment agencies of implementing Water Framework Directive investigations to determine significant damage at GWDTEs (Groundwater Dependent Terrestrial Ecosystems). Much of this work has been driven by various members of the 'Wetlands Task Team' of the Water Framework Directive UK Technical Advisory Group (WFD UKTAG). A three-tier approach to site investigation is described, providing suggestions for useful sources of information to inform both initial and detailed desk studies and subsequent site investigations. Both affordable and more expensive investigative methods are described; their usefulness in terms of contributing to a final site conceptual model are discussed. The need for long term monitoring to characterise baseline conditions and incorporate hydrological extremes (wet years and dry years) is demonstrated. A summary table provides a list of investigative methods scored on their cost, time required and contribution to conceptual understanding. The importance of both hydrogeologists and ecologists working together throughout the process is stressed and the 'ecohydrological site walkover' is proposed as a principal activity for any site investigation.

INTRODUCTION

GWDTEs (Groundwater Dependent Terrestrial Ecosystems) are wetlands which critically depend on groundwater flows and or chemistries (Schutten *et al* 2011). The Water Framework Directive (WFD) requires the identification of GWDTEs, risk screening and assessment of significant damage (Whiteman *et al* 2009). Significant damage can be caused by both quantitative and chemical groundwater pressures that result in unfavourable ecological condition under Habitats Directive (HD) assessments. The magnitude or significance of damage is related to the societal (conservation in UK) importance of the features of the wetland and the degree of change to these features resulting from the pressure (Schutten *et al* 2011).

If during the WFD assessment a groundwater body is classified at 'poor status' due to unfavourable condition at a GWDTE, related to a groundwater pressure, then an investigation is required to characterise the sources and pathways of groundwater mediated pressures. Whiteman *et al* (2009) argue that;

'this means shifting investigative focus somewhat away from, for example, single target water levels to a holistic consideration of water supply mechanisms and delivery or protection of wetland regimes including hydrological (groundwater level, groundwater flow, seepage, surface water flow), hydrochemical and site management'.

WFD investigations in England and Wales have been targeted at high risk sites defined using a tiered risk assessment procedure (e.g Whiteman *et al* 2010). The return of the GWDTE to favourable ecological condition must be realised if the associated groundwater body is to return to 'good status' and European WFD and HD targets achieved. Member States are required to achieve good groundwater body status by 2025. One of the significant challenges faced by practising hydrogeologists and ecologists in the UK in recent years has been assessment and investigation of groundwater impacts upon ecological receptors. Hydrogeologists are required to classify, characterise, risk screen and investigate groundwater mediated pressures that can cause significant damage (see Whiteman et al., 2010) to a range of designated GWDTE. Groundwater body status in England and Wales is assessed through five tests: a) overall resource balance: b) groundwater impacts upon dependent surface water bodies; c) risk of saline intrusion; **d) significant damage to groundwater-dependent terrestrial ecosystems (GWDTEs)** and e) overall groundwater body chemical quality.

This paper describes ecohydrogeological methods used to investigate and conceptualise wetlands that are considered to be at high risk of significant groundwater pressures.

Figure 1 Qualitative and quantitative pressures at GWDTE. Left: enriched vegetation at Dowrog Common (SSSI/SAC), Pembrokeshire Right: Drainage ditch at Cors Hirdre (SSI/SAC). Photograph with kind permission of Dr Peter Jones (NRW).

'WETLANDS TASK TEAM'

The wetlands community within the UK is supported by the 'Wetlands Task Team', part of the Water Framework Directive UK Technical Advisory Group (WFD UKTAG). This team is a partnership of the UK environment and conservation agencies and invited technical specialists. The 'Wetlands Task Team' is one of the nine groups that support the UKTAG, providing technical advice and guidance on the implementation and application of the WFD. The WTT reports to the UK wide WFD policy group drawn from of UK government administrations. The team comprises staff from Natural Resources Wales, Scottish Environment Protection Agency, Scottish Natural Heritage, Environment Agency, Natural England, Northern Ireland Environment Agency and the British Geological Survey. The free-to-download technical reports produced by the Wetlands Task Team provide a useful resource when considering how to apply the WFD to groundwater dependent wetlands (see UKTAG, 2004, UKTAG, 2012a and UKTAG, 2012b).

BEFORE YOU START

Two questions that need to be satisfied before starting any WFD investigation are:

- Is the site in unfavourable ecological condition (due to suspected groundwater pressures) as reported for the Habitats Directive (Habitats Directive)?
- Have the sites been assessed for significant damage, and scored as 'at risk' as part of the EU WFD Classification (Kimberly *et al* 2014 for Republic of Ireland and Farr & Wilson, 2013 for Northern Ireland).

If you can answer 'yes' to both of these questions then a WFD investigation is justified and you can move on to the tiered approach to site investigation.

A TIERED APPROACH TO SITE INVESTIGATION

In England and Wales a three tiered approach (Table 1) has been devised and is based upon on pilot work for the WFD by Buss & Hulme (2007) and more recently Brooks *et al* (2008). Investigations are most likely to be undertaken at sites that are in unfavourable ecological condition under the Habitats Directive and sites that have been assessed as being at risk of significant damage under the Water Framework Directive classification. The proposed tiered approach offers a simple step by step guide from initial characterisation (Tier 1), further characterisation (Tier 2) and evaluation and classification (Tier 3). This paper will concentrate on the more practice and field based 'Tier 3' that includes site visits and data collection.

	Tier 1	Tier 2	Tier 3
	Initial characterisation :basic desk study	**Further characterisation** :detailed desk study	**Evaluation and Classification** :site investigation and data collection
Where to look?	Site managers Local experts Published papers Grey literature Other reports Published maps	Ecological maps (NVC mapping) Geological maps Borehole archive Hydrometric archive Water chemistry archive Soil maps Modelling reports Ecology reports Air Pollution Inventory System	Ecohydrological site walk over On-site investigations: -subsurface investigation -Water levels -Water quality -Ecological observations
What to look for?	Local Expert knowledge Anecdotal evidence Known pressures Ecology (NVC mapping) Topography Geology & Soils Hydrogeology / Hydrology	Ecological data and NVC mapping Bedrock & Superficial geology Groundwater levels Groundwater quality Soil types and cover Surface water flow Atmospheric loading data	Surface water inflows Surface water outflows Groundwater discharge points: springs/flushes/seepages Flow rates of all water features Water level controls (.e.g weirs/ditches) Head difference between water features Near-surface geology Distribution of species / communities Enriched vegetation

Table 1 Three tiered approach to risk assessment of significant damage at GWDTE (modified from Brooks *et al* 2008).

TIER 1 AND TIER 2 (DESK STUDY)

Although the desk studies (Tier 1 & 2) are not the focus of this paper it is worth drawing the attention of the reader towards useful information within both the published and grey literature from the UK. During the last decade the effect of groundwater abstractions has been addressed by investigations undertaken as part of the EU Habitats Directive review of consents and other local impact assessment studies (e.g. Whiteman *et al* 2004; Whiteman *et al* 2009; Gellatly *et al* 2012). Further development of eco-hydrological guidelines for specific wetland habitats include: wet woodlands (Barsoum *et al* 2005), humid dune slacks (Davy *et al* 2010) and wet heaths (Mountford *et al* 2005) and more general lowland wetlands plant communities (Wheeler *et al* 2004). The Fen Management Handbook produced by Scottish Natural Heritage (SNH, 2011) is a wealth of practical information and. 'WETMECS' or wetlands water supply mechanisms are described in detailed in Wheeler *et al* (2009).

TIER 3 (SITE INVESTIGATION AND DATA COLELCTION)

ECOHYDROECOLOGICAL SITE WALKOVER

The 'ecohydrological site walkover' is perhaps the most important stage of any investigation. In simple terms it should involve a hydrogeologist and an ecologist, preferably both of whom should have good local knowledge. The site walkover gives both parties the chance to discuss and share information and to consider how hydrological processes may support and also transmit a range of pressures to ecological receptors. Using the **source-pathway-receptor** concept that is familiar to hydrogeologists, both potential sources and pathways for groundwater mediated pressures should be discussed. During the site walkover the ecologist should identify **receptors** (e.g. vegetation) that are deemed to be in unfavourable condition. In response the hydrogeologist should be looking at the landscape and considering what the **sources** and **pathways** of the pressures could be. An example of the source-pathway-receptor concept is provided: diffuse agricultural pollution (source) is transmitted by groundwater (pathway) leading to nutrient enrichment and unfavourable condition of a designated site (receptor). Information collected during this process should include: notes on the vegetation condition, basic readings of water levels and flow, water chemistry and identification of landuse pressures within the immediate and wider catchment. Even at this initial stage both the hydrogeologist and ecologist are starting to gather information that can be combined to inform an ecohydrological conceptual model. It is important for these thoughts and observations to be recorded. The site walkover will highlight the knowledge gaps that can be answered with further on site investigation.

Figure 2 Hydroecological site walkovers should include an experienced hydrogeologists and ecologist (only one of each required). This photograph shows a wetlands hydrology training course lead by Dr Rob Low at Cors Bodeilio (SSSI/SAC/NNR), Anglesey.

GEOLOGY AND THE NEAR SUBSURFACE

It is likely that characterisation of the subsurface may form part of any site investigation, providing geological information to inform an initial site conceptual model. In England and Wales a range of methods have been used that range in time, complexity and cost. At the most affordable end is the hand auger (
Figure 3). Operated manually it can retrieve small samples of unconsolidated material from 0-3 meters below the surface, however its operational depth can be limited by resistant materials such as clays, cobbles and bedrock. Obtaining detailed cores for stratigraphical logging can be achieved using small portable percussion drills, such as the Dando (
Figure 3) that is capable of reaching a depth of almost 20 meters and can cope with stiff clays, larger cobbles and less competent bedrock. Larger percussion and rotary rigs can reach greater depths however their use is limited by their size and ability to gain access to the desired areas within the designated site. Before drilling it would be advisable to address the following questions: is the site or are the designated features too sensitive for a drilling operation? Is the surface competent enough to support and allow safe access for the drill rig?

Not all subsurface investigations need to be intrusive and geophysical methods provide further options for site conceptualisation; a useful example comes from Wybunbury Moss, Cheshire (Environment Agency, 2011 and Brooks *et al* 2011). Large-scale application of geophysics is likely to be more costly than shallow drilling and hand auguring, and it is able to provide information on a wider and more laterally continuous section across a given site. Geophysics can also help inform where best to site intrusive investigations, and in an ideal world one may wish to undertake geophysical surveys prior to any drilling operation, however the cost of this approach is prohibitive. More recently aerial geophysical datasets have been used to infer hydrological and ground conditions over larger areas containing several wetlands (e.g Beamish & Farr, 2013) and for the landscape scale mapping of peat bodies (Beamish, 2014).

Figure 3 Left: Dr Mark Whitman (EA) uses a hand auger to collect information on the near surface deposits at Cors Geirch. Right: Stephen Thorpe (BGS) uses a Dando percussion drill to obtain an 18m core from Tregaron Bog.

WATER LEVEL AND FLOW

For many wetland sites characterisation of both surface and groundwater levels may be required to improve a site conceptual model. Several monitoring options have been used in England and Wales and these vary in terms of cost, time and complexity. Simply installing a dipwell or borehole is not going to answer your questions, it must be designed, located and the data interpreted for it to yield useful information. The siting of any water level monitoring should be carefully considered, groundwater monitoring should where possible be associated with known NVC communities. Several boreholes may be required if you want to infer groundwater flow directions, or 'nested piezos' if you are interested in the vertical movement of groundwater.

The most affordable method of groundwater level monitoring is the 'dipwell' (Figure 4). Constructed of 1m length, 50mm diameter PVC pipes that can be joined together, these wells can be installed using basic manual tools to a depth of 2-3m depending on the nature of the subsurface. Geotextile membrane of varying pore size can be fitted to the slotted section to allow for monitoring in a range of environments from peat to fine sands. Shallow dipwells may need to be anchored to stop movement; this can be achieved by using a metal earth anchor attached to a more stable underlying area such as a basal clay or bedrock. Experiences from Dowrog Common (Pembrokeshire) showed that unanchored piezometers and wells experienced movement of several cm's over the period of one year, lifting concrete headworks from the ground. The solution was to anchor the dipwells to the basal clay unit using a thin metal rod attached to the dipwell. Where surface water features such as ditches require monitoring then the same dipwell casing can be used to construct stilling wells. If deeper monitoring is required then portable drills or larger percussion rigs (Figure 4) can be used to drill boreholes, although access problems, especially where the terrain is very soft, wet or inaccessible are likely to be limiting.

Figure 4 Left: affordable dipwells can be installed by hand to a depth of 2-3meters in unconsolidated materials (Rhoswen Leonard and Janine Guest). Middle: slightly more expensive power hand drill can install to a greater depth and through more competent materials. Right: a large percussion drill can install a borehole or piezometer into more competent bedrock (photograph Dr Peter Jones).

Once the monitoring wells are in place they should be surveyed to a datum, preferably meters above Ordnance Datum (maOD). Groundwater levels can be recorded using a manual dip meter or by installation of a digital pressure transducer. Manual dipping is initially a lower cost option however once time is taken into account then it can become very expensive and data records are likely to show only general trends, with any changes in water level between visits not recorded. Pressure transducers are manufactured by a range of companies and their small size often allows insertion into dipwells <30mm in diameter, some transducers now come with a 2m range allowing a better resolution of data from small scale water level changes often associated with wetlands. The transducers can be set to record both pressure and water temperature at various intervals, and experience from England and Wales suggests an hourly frequency provides a suitable baseline data record for most wetlands. During a pump test at Greywell Fen, Hampshire (Low *et al* 2013) a 15-minute interval was chosen to record sub hour changes in response to changes in the pumping regime. Pressure transducers can also be used for monitoring surface water features such as drains, ditches, lakes and turloughs (e.g. Farr *et al* 2012) .Hydrometric water level data is often plotted as a time series against rainfall events however cumulative frequency curves which illustrate the period of time a water levels spends at a set level are also a useful output.

Measurements of surface water flow can be achieved by the installation of weirs or by direct gauging. Water level data from stilling wells can be converted using stage-discharge relationships. Ephemeral springs and diffuse seepage areas are much more difficult to measure. Spring flow can be measured using a simple ‘bucket and stop watch’ method which provide individual spot readings

Figure 5). Installation of temperature or electrical conductivity meters in springs or areas of diffuse flow can provide records of when discharge occurs or when the sites are dry, however conversion to volumetric flow is not simple. Researchers in the U.S have successfully used electrical resistivity sensors to measure diffuse and ephemeral flow in a range of settings (see Bhanjee & Lindsay, 2011 and references therein) and these techniques could be applied to characterise diffuse or topogenous flow into and within GWDTEs in the UK and the Republic of Ireland.

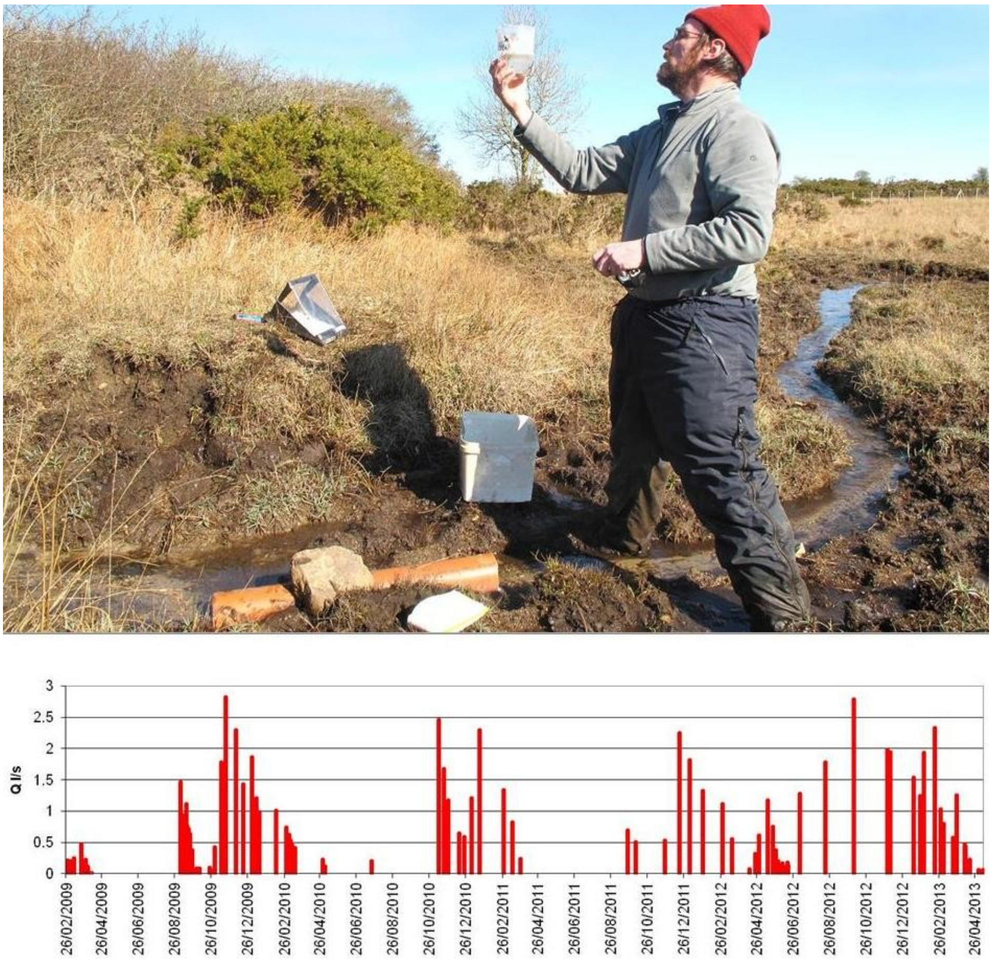

Figure 5 ‘Bucket and stopwatch’ method for gauging flow of an ephemeral spring (data with kind permission of Dr Peter Jones, Natural Resources Wales)

WATER QUALITY

Collecting representative samples is not always straight forward, especially as many wetlands experience diffuse groundwater discharge at their margins and widespread shallow rheo-topogenous flow within the sites. Discrete springs, boreholes or dipwells may provide easier sampling locations. Before simple methods for collection of representative samples are discussed we must consider what determinands should be analysed. Discrepancies between analyses from one wetland to another were identified in early WFD investigations in England and Wales. Analysis may vary in terms of the total number of determinands and also between their limits of detection (LOD). It was decided that a standardised analysis suite should be proposed allowing conservation bodies and environmental regulators to collect comparable water quality information, the standard analysis suite is presented in Table 2. The proposed suite is not definitive and can be changed and tailored to specific investigations. It covers major ions used to type groundwater (e.g. Ca, Mg, Na, K, Cl, SO_4 and $HC0_3$), field parameters (temperature, electrical conductivity, dissolved oxygen and Eh) and nutrients (nitrate, phosphate etc).

Useful equipment for obtaining representative samples from wells includes: 12v specialist submersible pumps, and the very light and more affordable suction 'caravan pumps' which can lift water from just a few meters and are easy to transport across large sites (Figure 6). A stainless steel jug is indispensible for lowering into surface water features and for collecting shallow topogenous flow (Figure 6). Field parameters such as temperature, pH and dissolved oxygen should always be recorded in situ whenever possible and 50mm diameter dipwells allow most multiparameter sondes to be lowered into them. If this is not possible flow through cells should be used or the probes submerged in flowing water on the surface of the site.

	ALKALINITY PH 4.5 - $CACO_3$	AMMONIA - N	BICARBONATE - HCO_3	CALCIUM - Ca	CHLORIDE ION - Cl	CONDUCTIVITY @ 25C	HARDNESS TOTAL - $CaCO_3$	IONIC BALANCE (ANIONS/CATIONS)	IRON - Fe	MAGNESIUM - Mg	MANGANESE - Mn	NITRATE - N	NITRITE - N	NITROGEN TOTAL OXIDISED - N	ORTHOPHOSPHATE - P	OXYGEN DISSOLVED-SITU	OXYGEN DISSOLVED - SITU	pH IN SITU	Phosphate	POTASSIUM - K	SODIUM - Na	SULPHATE - SO_4	TEMPERATURE	Redox Potential in Situ	Iron Dissolved	Manganese Dissolved
Units	mg/l	mg/l	mg/l	mg/l	mg/l	uS/cm	mg/l	%	ug/l	mg/l	ug/l	mg/l	mg/l	mg/l	mg/l	mg/l	%	pH	mg/l	mg/l	mg/l	mg/l	CEL	Mv	ug/l	ug/l
Limit of detection	5	0	-	1	1	-	-	-	30	0.3	10	-	0.004	0.2	0.02	-	-	-	0.02	0.1	2	10	-	-	-	-

Table 2 Standardised water quality analysis suite for groundwater dependent ecosystems

Figure 6 Left: an affordable 12v 'caravan pump' is lowered into a dipwell to obtain a sample. Middle: Les Colley and Adam Daniel use a stainless steel jug to collect water from a ditch Right: Jon Hudson collects a water quality sample from a diffuse seepage zone.

A range of novel groundwater quality techniques have been used to define the sources of nutrients and the travel time (or age) of groundwater reaching springs and seepages at various wetlands (Table 3). These methods complement the more traditional water quality analysis improving the site conceptual model.

Nitrogen and oxygen stable isotopes can help to determine the source of nitrogen dissolved in groundwater. The method works by comparing the ratios of the respective isotopes, ^{15}N to that of air ($\delta^{15}N$ ‰) and ^{18}O relative to Vienna Standard Mean Ocean Water ($\delta^{18}O$ ‰). The analysis can help to 'fingerprint' various sources of nitrogen including, soil organic matter, inorganic fertilizers and atmospheric deposition.

Chlorofluorocarbon (CFC) and sulphur hexafluoride (SF_6) can be used as tracers to date water up to 50 years old, to infer groundwater mixing and provide indicators of likely groundwater flow mechanisms (Gooddy *et al* 2006). Two results are presented in Table 3 alongside the nitrogen and oxygen stable isotope analysis. The results are used to infer a year of recharge for each sample, showing that in both cases there is a mixing of younger and older water.

Monitoring point	δ^{15} NNO3 (‰)	δ^{18}ONO3 (‰)	**Nitrogen Source**	**CFC-12 pmol/l**	**CFC-11 pmol/l**	**SF_6 fmol/l**	**CFC-12 pmol/l**	**CFC-11 pmol/l**	**SF_6 fmol/l**	**Year of recharge (range of values)**
SPRING 1	8.1	4.8	Nitrification of soil organic nitrogen	**2.9**	**4.4**	**2.2**	**0.98**	**0.84**	**0.81**	**1984-2002**
SPRING 2	7.6	3.8	Nitrification of soil organic nitrogen	**3.4**	**5.1**	**2.1**	**1.17**	**0.99**	**0.8**	**1987 - Modern**

Table 3 Examples of novel groundwater quality analysis to inform site conceptualisation at GWDTEs

HYDROLOGICAL EXTREMES AND THE NEED FOR LONG TERM MONITORING

It is important that the classification process for the WFD is based on long term data sets. Individual water quality samples or water level readings are useful as part of one-off investigations and can contribute to baseline datasets, but they do not allow us to identify seasonal or long term variations and trends (Farr *et al* 2014 in press). A complete annual cycle is suggested as the minimum duration of recording for water levels and quality, but even this has obvious risks in that some years are very wet and others much drier. It is difficult to define what is meant by 'long term' monitoring. A minimum of 5 years may be required to characterise hydrological extremes e.g. wet years and dry years. To detect longer term changes related to the changing climate even longer records (>20 years), such as those collected from Ainsdale sands (Clarke, D and Sanitwong Na Ayuttaya, 2010) may be required.

CONCLUSIONS

WFD investigations in England and Wales have produced a wealth of information that can be readily used by other regulatory and conservation bodies. Examples from England and Wales include Wybunbury Moss (Environment Agency, 2011) Cors Bodeilio and Merthyr Mawr (SWS, 2010a) and Cors Erddreiniog (SWS, 2010b). We have attempted to score the investigative methods by considering their cost (e.g. equipment, plant hire etc), duration (e.g. labour costs and ongoing monitoring) and ultimately their contribution to a better conceptual understanding (Table 4). The table is provided as a guide only and we recognise that the order may change depending upon the type of pressure and GWDTE, however in all cases the ecohydrological site walkover should remain at, or close to the top of the table.

		Cost			Duration			Conceptual Understanding		
		<£1K	£1-5K	>£5K	1 Month	1 year	> 1 year	Low	Medium	High
Ecohydrological site walkover		■			■					■
Local expert knowledge		■			■					■
Catchment audit		■			■				■	
Ecological surveys	Short term	■			■				■	
(NVC and quadrats)	Long term			■			■			■
Groundwater quality	Short term	■	■		■	■			■	
	Long term			■			■			■
	In situ		■			■			■	
Surface water quality	Short term	■	■		■	■			■	
	Long term		■				■			■
Shallow intrusive investigation (auger)		■			■				■	
Drilling	Shallow		■		■					■
	Deep			■	■					■
Groundwater levels	Short Term	■			■				■	
	Long Term			■			■			■
Surface water hydrology	Short Term		■		■				■	
	Long Term			■			■			■
	Nitrogen/ Oxygen isotopes		■		■				■	
Novel geochemical analysis	Age dating (e.g CFC/SF_6)		■		■				■	
Atmospheric loading (www.apis.ac.uk)		■			■				■	
Historic aerial photography		■			■				■	
Remote sensing				■		■			■	
Geophysical surveys			■		■				■	
Airborne geophysical survey				■		■		■		
Flow/nutrient modelling			■			■			■	
Groundwater model				■			■			■
Multi-disciplinary review		■			■					■

Table 4 Investigative methods for GWDTE in England and Wales, rated in terms of cost, time and ultimately their contribution to an ecohydrological conceptual model. (n.b it has not been possible to discuss all of the methods listed in this table within this paper).

ACKNOWLEDGMENTS

There a numerous people to thank including, but not limited to: Justin Hanson, Janine Guest and Rhoswen Leonard of the NRW Anglesey and Llyn Fens LIFE team, Les Colley, Jonathan Hudson and Rachel Breen of NRW. The UKWFD TAG 'wetlands task team' including, Dr Hans Schutten, Iain Diack, Natalie Phillips, Anna Wetherell, Ann Skinner, Andrew McBride and Emma Goodyear. Dr Rob Low (Rigare Ltd) and Paul Inman. This paper is published with the permission of the Executive Director, British Geological Survey (NERC).

REFERENCES

Barsoum, N., Anderson, R., Broadmeadow, S., Bishop, H, & Nisbet, T.2005. Ecohydrological guidelines for wet woodland – Phase I. English Nature Research Reports Number 619. http://publications.naturalengland.org.uk/publication/91054

Beamish, D. 2014.Peat Mapping Associations of Airborne Radiometric Survey Data. *Remote Sensing*. 2014; 6(1):521-539. http://www.mdpi.com/2072-4292/6/1/521

Beamish, D, & Farr, G., 2013. Airborne Geophysics: a novel approach to assist hydrogeological investigations at groundwater dependent wetlands. *Quarterly Journal of Engineering Geology and Hydrogeology.* V46: p54-62. http://nora.nerc.ac.uk/500309/

Bhamjee, R & Lindsay, J.B. 2011. Ephemeral stream sensor design using loggers. Hydrol. Earth System Sci., 15, 1009-1021. http://www.hydrol-earth-syst-sci-discuss.net/7/6381/2010/hessd-7-6381-2010.pdf

Brooks, A., Whiteman, M., Skinner, A., Farr, G., Papaioannou, A, Coffey., A, Bellis, L, Jones, P & Low, R. 2011. Investigation of diffuse groundwater chemical impacts on groundwater dependent terrestrial ecosystems in England and Wales: implications for WFD groundwater body classification and programmes of measures. HydroEco, 2011, May 2-5th 2011. http://web.natur.cuni.cz/hydroeco2011/download/presentations/oral/SWFD/6_240_Brooks_HydroEco_2011_final_240.pdf

Buss, U & Hulme, P.2007. Testing UKTAG guidance for the identification of groundwater dependent terrestrial ecosystems in the Ribble Basin. Environment Agency of England & Wales report SCHO0407BMNG-E-P. http://cdn.environment-agency.gov.uk/scho0407bmng-e-e.pdf

Brooks, A., Cohen, A., Evers, S., Hulme, P & Phillips, N.2008. Methodology for the assessment of significant damage at wetlands. Environment Agency Science Report SC030285. https://publications.environment-agency.gov.uk/skeleton/publications/ViewPublication.aspx?id=ef289b1e-1e14-4e73-84f4-8ac1581d2258

Clarke, D and Sanitwong Na Ayuttaya, S (2010). *Predicted effects of climate change, vegetation and tree cover on dune slack habitats at Ainsdale on the Sefton Coast.* UK.Journal of Coastal Conservation, 14, (2), 115-125.

Davey, A.J., Hiscock, K.M., Jones, M.L.L., Low, R., Robins, N.S & Stratford, C. 2010. Ecohydrological guidelines for wet dune habitats. Environment Agency Science Report GEH00310BSGV. http://cdn.environment-agency.gov.uk/geho0310bsgv-e-e.pdf

Environment Agency, 2011. Refining river basin planning through targeted investigations on GWDTE, Wybunbury Moss.

Farr, G & Wilson, P. 2013. EU Water Framework Directive: 2nd cycle characterisation of groundwater dependent terrestrial ecosystems in Northern Ireland. British Geological Survey Commissioned Report for NIEA. CR/14/046.

Farr, G., Hatton-Ellis, T., Jones, D.A., Lambourne, C., Bevan, J & Naughton, O. 2012. Hydrology, water quality and condition of Pant-y-Llyn, Wales' only turlough. Countryside Council for Wales (CCW) Staff Science Report No. 12/8/1.

Farr, G., Whiteman, M., Jones, P. S & Breen, R. 2014. Wetlands and the Water Framework Directive: Key challenges for achieving good ecological status at the Angelsey and Llŷn

Fens SACs. In Restoring Alkaline and Calcareous Fens within the Anglesey and Llyn Fens SACs in Wales: Report of the Project Conference 9-11 October 2013. Eds: P.S. Jones, J. Hanson & J. Guest. [in press]

Gellatly, S. C., Raynor, M. E., Green, C. J. E. & Neve, P. S. 2012. Using and refining an existing regional groundwater model to assess the impacts of an abstraction on a nearby wetland. In: Shepley, M. G., Whiteman, M. I., Hulme, P. J. & Grout, M. W. (eds) Groundwater Resources Modelling: A Case Study from the UK. Geological Society, London, Special Publications, 364, 333–351

Gooddy, D.C., Darling, G.W, Abesser, C & Lapworth, D.J. 2006. Using Chloroflurocarbons (CFCs) and Sulpher Hexafluoride (SF_6) to characterise groundwater movement and residence time in a lowland chalk catchment. *Journal of Hydrology*, 330 (1-2). 44-52 http://nora.nerc.ac.uk/4481/

Kimberly, S, Naughton, O and Regan, S. 2014. Assessing significant damage to selected Irish Groundwater Dependent Terrestrial Ecosystems (GWDTE) types as part of Groundwater Body Classification under the EU water framework Directive. IAH Proceedings 2014 [previous paper in this conference]

Low, R., Morris, S., Hutchings, A., Harfoot, H & Goodard, E. 2013. Ecohydrological impact assessment, Greywell Fen, Hampshire. Poster presented at the Groundwater Dependent Ecosystems meeting of the Geological Society of London, Birmingham and Midlands Institute, 27th February, 2013.

Mountford, J.O., Rose, R.J. & Bromley, J. 2005. Development of eco-hydrological guidelines for wet heaths – Phase 1. English Nature Research Reports Number 620. http://publications.naturalengland.org.uk/publication/107007

Schutten, J., Verweij, W., Hall, A., & Scheidleder, A. 2011. Technical Report on Groundwater Dependent Terrestrial Ecosystems (GWDTEs). Technical report to European Working Group C – Common Implementation Strategy Working Group on Groundwater.

SNH (Scottish Natural Heritage). 2010. *The Fen Management Handbook*, (2010), Editors A. McBride, I. Diack, N Droy, B. Hamill, P.Jones, J. Schutten, A. Skinner, and M. Street. Scottish Natural Heritage, Perth. http://www.snh.gov.uk/about-scotlands-nature/habitats-and-ecosystems/lochs-rivers-and-wetlands/fen/

SWS (Schlumburger Water Services). 2010a. Report on targeted risk-based investigations on selected Welsh Groundwater Dependant terrestrial Ecosystems (Cors Bodeilio and Merthyr Mawr). For Environment Agency.

SWS (Schlumburger Water Services). 2010b. Desk Study Cors Erddreiniog Investigations on selected Welsh Groundwater Dependent Terrestrial Ecosystems (GWDTEs). November 2010. 1-274/R3 FINAL. For Environment Agency.

Wheeler, B.D, Gowning, D.J.G, Shaw, S.C, Mountford, J.O and Money, R.P. 2004. Ecohydrological guidelines for lowland wetlands plant communities. Eds Brooks A.W, Jose, P.V and Whiteman M.I. Environment Agency Report. http://www.floodplainmeadows.org.uk/files/floodplain/d96435.pdf

Wheeler, B.D., Shaw, S & Tanner, K. 2009. A wetland framework for impact assessment at statutory sites in England and Wales. Intergrated catchment science programme. Science report: SC030232. http://www.floodplainmeadows.org.uk/files/floodplain/d96435.pdf

Whiteman, M.I., José, P., Grout, M.W., Brooks, A., Quinn, S.A., Acreman, M. 2004. Local impact assessment of wetlands – from hydrological impact to ecological effects. Paper presented at the 2nd British Hydrological Society International Conference, Imperial College, London, 12-16 July 2004. In: *Hydrology: Science & Practice for the 21st* Century, Proceedings of 2nd British Hydrological Society International Conference, Imperial College London 12-16 July 2004, Volume 2, 198-212.

Whiteman, M.I., Wheeler, B.D., Shaw, S.C., Lewis, T., Grout, M., Tanner, K. 2009. Use of WETMECS typology to aid understanding of groundwater-dependent terrestrial ecosystems in England and Wales. In: Quevauviller, P., Fouillac, A.M., Grath, J., Ward, R. (Eds.), Groundwater Quality Assessment and Monitoring. John Wiley & Sons, pp. 259–272.

Whiteman, M., Brooks, A., Skinner, A. Hulme, P. 2010. Determining significant damage to groundwater dependant terrestrial ecosystems in England and Wales for use in implementation of the Water Framework Directive. Ecological Engineering, 36, p1118-1125.

UKTAG. 2004. United Kingdom Technical Advisory Group on the Water Framework Directive. Guidance on the identification and risk assessment of Groundwater dependent terrestrial ecosystems. Version 5 (21.01.04) http://www.wfduk.org/sites/default/files/Media/Characterisation%20of%20the%20water%20environment/Risk%20assessment%20of%20terrestrial%20ecosystems%20groundwater_Draft_210104.pdf

UKTAG. 2012a.United Kingdom Technical Advisory Group on the Water Framework Directive. Technical report on groundwater dependent terrestrial ecosystem (GWDTE) threshold values. (Version 8) 23.03.2012. http://www.wfduk.org/sites/default/files/Media/Environmental%20standards/GWDTE%20chemical%20values_Final_230312.pdf

UKTAG. 2012b. Paper 11b(i) Groundwater Chemical Classification for the purpose of the Water Framework Directive and the Groundwater Directive. (Version 0.8) Feb 2012. http://www.wfduk.org/sites/default/files/Media/Assessing%20the%20status%20of%20the%20water%20environment/GWChemical%20Classification_FINAL_2802121.pdf