LoPro – The Value of Low Yield Aquifers

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Abstracts

An overview of low productivity bedrock aquifers in Scotland – classifying and understanding in order to manage.

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Work carried out over the last 7 years by BGS in conjunction with SEPA has helped map out where the low productivity aquifers in Scotland are and started to classify them in terms of their physical and chemical properties. It has also helped to highlight the gaps in understanding of these widespread and widely used aquifers, and moved us closer to managing them effectively.

Low productivity aquifers in Scotland are used for private and public water supplies, and provide an essential environmental function in sustaining river baseflows.

Transmissivity, specific capacity and storativity data for Scotland's low productivity aquifers are sparse, but many more values for borehole yields are available, and statistical analysis shows that in Scotland, yield is a good proxy for transmissivity (Graham et al 2009).

Groundwater flow systems in low productive aquifers are starting to become clearer through groundwater chemistry and residence time analysis. New data from southern Scotland and Aberdeenshire show there can be relatively long residence times of up to several decades; groundwater chemistry is variable, controlled by bedrock and overlying superficial deposit lithology and to compartmentalised flow systems; and nitrate concentrations are also highly variable due to compartmentalism and to the influence of local land use, rather than regional flows.

These aquifers are mostly fractured with thin superficial covers, and are therefore highly vulnerable, but compartmentalised flow systems mean contamination is unlikely to spread far, raising different management issues to those faced by large regional aquifers.

This talk provides a rapid overview of what we know about Scotland's low productivity aquifers and highlights some of the main areas for improving our understanding.

Undertaking Pumping Tests in Low Yield Aquifers

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To assess the hydrogeological characteristics of low yield aquifers the challenges of accurate measurement of groundwater levels and groundwater discharge need to be met in addition to appropriate test result analysis (for example Aquiferwin32). Pumping tests have long been used as a successful method to investigate well yields and determine the hydraulic properties of an aquifer. The principle for low yield aquifers remains the same however; a high degree of accuracy and high resolution of groundwater level measurements becomes more important when flow rates are low. In addition the methods for monitoring flow rates during pumping tests must be tailor-made to the anticipated yields from the tests. Project experience undertaking pumping tests at rates of 2 – 400 litres/minute has shown that particularly at the low end of the scale these are significant issues.

Telemetric pressure transducers were able to achieve an accuracy of 1mm and have the capacity to achieve a monitoring resolution of 10 seconds over a long time period (and allow online viewing of real-time data). With low flow rates drawdown may be minimal in some observation wells and factors such of minor precipitation events or atmospheric pressure changes must be able to be easily eliminated from the datasets so that drawdowns due to groundwater pumping can be identified. Drawdown may initially occur rapidly then become smaller and smaller however the cone of depression is still expanding. The level of accuracy and measurement resolution given by the telemetric transducers allow for this to be properly assessed ensuring pumping tests are not terminated prematurely before steady-state conditions are reached.

Undertaking pumping tests with such a wide variation in pumping rates involved utilising a range of pumps and designing the best combination of equipment to monitor the pumping tests and gather meaningful datasets.

In addition to utilising the appropriate equipment set-up the same key principles of correct well installation and well development are also crucial to undertaking successful pumping tests and achieving maximum sustainable yields from low yielding aquifers.

Monitoring Poorly Productive Aquifers in the Republic of Ireland

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'Poorly productive' aquifers (PPAs) underlie ~65% of the land surface of the Republic of Ireland. Although PPAs do not contain significant groundwater resources, they are nonetheless important for private and small-scale water supplies, local streams, and groundwater-dependent terrestrial ecosystems. As such, PPAs have to be included in the monitoring for Water Framework Directive (WFD) purposes.

Because of their low transmissive nature, detailed hydrogeological assessments of PPAs have seldom been carried out. The holistic, integrated approach to water management required by the WFD has therefore resulted in a reappraisal of the role that PPAs may have in discharging pollutants to rivers, lakes and wetlands via shallow groundwater pathways. Consequently, the EPA decided to install a high-quality monitoring network specifically aimed at providing an improved hydrogeological understanding of PPAs in terms of their physical, hydraulic and hydrochemical characteristics.

Six surface water catchments with weir structures were selected for study. The catchments represent a range of rock types (granite, Precambrian gneiss, Dalradian metasediments, Devonian Old Red Sandstone, Ordovican metasediments and Dinantian impure limestones) and land-uses (forestry, low intensity sheep grazing and managed grassland). In each catchment, up to 12 monitoring wells were installed at three clusters along a transect which runs perpendicularly to the alignment of the nearby stream or river. Data loggers have been installed to monitor groundwater levels and samples are taken on a quarterly basis for chemical and bacteriological analyses.

The presentation will outline the development of the conceptual model for these aquifers, the selected monitoring approach, and discussion of the results of work undertaken to-date.

Multi-disciplinary characterisation of groundwater flow regimes in low productivity hardrock aquifers

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Development of realistic numerical models of groundwater flow in hitherto rarely studied Irish low productivity fractured bedrock aquifers require a realistic conceptual basis. Field research

completed under the Griffith Geoscience Programme aims to develop a sound understanding of the controls on groundwater flow regimes in hardrock aquifers across Ireland, based on investigations carried out at four EPA/GSNI instrumented catchments, underlain by bedrock that has experienced contrasting levels of post-depositional deformation. Pumping test results and geophysical logging data (caliper and high resolution acoustic televiewer probes) reveal high levels of inter-borehole hydraulic heterogeneity and associated fracture density. Steeply dipping conductive fracture sets can impart high levels of anisotropy and hydraulic isolation between shallow and deep monitoring wells at given locations. This is further borne out by hydrochemical analyses of samples collected from well clusters that indicate significant contrasts in water quality with depth. Increases in SiO_2 content, pH and EC suggest water generally increases in age with depth, with deeper groundwaters approaching chemical equilibrium with poorly reactive minerals. Surface geophysical surveys, employing geoelectric and electromagnetic techniques, continue at the time of writing and promise to provide further insight into the three dimensional spatial variability of hydrogeological properties across the study areas away from groundwater monitoring points. Research findings to date point towards the importance of weathering at the overburden/bedrock interface in influencing aquifer storage. Relatively high volumes of water stored in this transition zone may buffer fluctuations in head and thus discharge rates to receiving surface water bodies. Results are broadly consistent with concepts employed by EPA and GSNI in developing monitoring networks, although investigations into the impact of spatial heterogeneity across catchments on groundwater flow promises to shed further light on this issue and reveal how representative existing monitoring points are for reflecting catchment-wide hydrogeological processes.

Methods for measuring the permeability of low permeability superficial deposits

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Groundwater flow and storage in low productivity superficial deposits is fundamental to the functioning of many catchments and can have a large impact on hydrogeology. However, estimating the permeability of these heterogeneous deposits can be problematic where insufficient insitu measurements are available from pumping tests in piezometers. Consequently, common practice is to estimate permeability from the material description or, where available, particle size distribution using a formula such as Hazen. In this study we developed a method of measuring permeability using a Guelph permeameter and applied it to a catchment in Morayshire, northern Scotland. Information on grain size and density was also collected. The catchment was heterogeneous, typical of many glaciated catchments, with superficial deposits comprising glaciofluvial deposits, glacial tills and moraines, and raised marine deposits and blown sands. Thirty-eight sites were investigated: permeability measurements were made using repeated Guelph permeameter measurements; density was estimated insitu by measuring cone resistance; the material was described using BS5930; and samples were taken for particle size analysis.

The method developed for directly measuring permeability using the Guelph permeameter gave consistent and repeatable results and also allowed good geological control over the measurements. It shows good promise for becoming an effective and efficient method of estimate permeability of superficial deposits.

Overall hydraulic conductivity in the Morayshire catchment varied from 0.001 m/d to > 40 m/d; glacial till had the lowest K (median 0.027 m/d) and glacial moraine the highest (median 30 m/d). However, within each geological unit there was great variability in measured hydraulic conductivity.

Multiple linear regression of the permeability and engineering data indicated that logd10 and density (measured by field description or cone penetration) were independent predictors of logK and together gave a relationship with an R^2 of 0.8. Therefore, in heterogeneous catchments, the permeability of superficial deposits is best estimated by measuring the finest fraction (d10) and also the density (how compact) the material is. Material description of the coarsest fraction of material (e.g. sand or gravel) had little predictive power.

Groundwater surveys in PreCambrian and Carboniferous aquifers (Anglesey) to implement Water Framework Directive monitoring, improve conceptual understanding, and provide baseline chemical data for GWDTE investigations.

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A promising start to the understanding of the hydrogeology of Anglesey was made when Greenly published his memoir in 1919, urging the reader to collect '*all available analysis*' so that '*the water problem of Anglesey will eventually be solved*' [1]. Little more was undertaken for the remainder of the twentieth century [2].

More promisingly the early part of the twenty-first century saw two surveys on the Precambrian Gwna formation and the Carboniferous Limestone sequence, undertaken between 2007-2008 [3a-b].

The surveys aimed to collect as much data as possible. Data was collated and site visits were undertaken to collect information including flow rates, chemistry and in some cases CFC/SF6 analysis.

Three groundwater monitoring boreholes were drilled into the Carboniferous Limestone sequence to provide groundwater level and quality data.

In general the groundwater quality in both aquifers is good, with generally low nitrates and little organic pollution. Groundwater is mostly used for private water supply. No significant abstractions were encountered, with $10m^3$/day being the highest figure quoted in the Carboniferous Limestone.

Two GWDTE's of significant importance (Cors Bodelilo and Cors Erdderiniog) are located on the Carboniferous Limestone. Chemical baseline data and conceptual understanding of the aquifer as a whole provided a basis for further study at these GWDTE sites.

1 Greenly, E. 1919. *The Geology of Anglesey.*

2 Robins & McKenzie. 2005. *Groundwater occurrence and the distribution of wells and springs in pre-Cambrian and Palaeozoic rocks, NW Anglesey.* QJEH, 28, 83-88.

3a WMC, 2007. Groundwater Quality and Supply Survey for the PreCambrian Gwna Group, Anglesey. For Environment Agency Wales.

3b WMC 2008. Groundwater Quality and Supply Survey for the Carboniferous Limestone, Anglesey. For Environment Agency Wales.

Investigation of diffuse groundwater chemical impacts on groundwater-dependent terrestrial ecosystems in Wales: Implications for WFD significant damage assessments.

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Two Groundwater-dependent Terrestrial Ecosystems (GWDTE's) of international importance (Cors Bodelilo and Cors Erdreinniog) are located on the Carboniferous Limestone in Anglesey (North Wales). Chemical baseline data and conceptual understanding of the aquifer as a whole provided a basis for further study at these GWDTE sites. Procedures for risk screening and assessment of significant damage to GWDTEs for EU Water Framework Directive (WFD) implementation have been developed by the Environment Agency for England and Wales[123] (Hulme *et* al 2007; Brooks *et al* 2009; Whiteman *et al* 2010).

Field investigations have been undertaken at Cors Bodeilio and Cors Erdreinniog to test the procedures, and to improve our ability to detect significant damage and help with prevention of further deterioration in groundwater status. This paper reports the results of these investigations, which focus on diffuse groundwater chemical impacts, and their implications for significant damage assessments, research needs and policy implementation in the second cycle of WFD river basin planning.

Investigations have been based on a source-pathway-receptor approach, quantifying these linkages at each site. Multiple sources and pathways of nitrates have been demonstrated by a combination of techniques, including high resolution logging of multilevel piezometers, combined with hydrochemical and nitrogen isotope sampling, hydro-ecological surveys and ecological mapping. At each stage of the investigation, the eco-hydrological conceptual model has been reviewed and updated by a multidisciplinary team of ecologists and hydrogeologists.

The results suggest that a combination of risk screening methods and targeted site-based data analysis will be required to ensure good status of WFD groundwater bodies in future river basin cycles. Site specific chemical data are required, along with knowledge of hydrological and chemical thresholds to trigger detailed assessment of significant damage. Multiple sources and pathways may contribute in combination to eutrophication- related impacts or damage, making impact assessment more complex.

[1] Hulme, P., Miller, F., Evers, S., Phillips, N., Brooks, A., Whiteman, M. and Cohen, A., 2007. Assessing the risk of significant damage at groundwater-dependent terrestrial ecosystems in England and Wales. In: Ribeiro, L., Chambel, A. and Condesso de Melo, M.T. (Eds.) Proceedings of XXXV IAH Congress "Groundwater and Ecology", Lisbon, September 11-15 2007.

[2] Brooks, A., Brown, R., and James, S., 2009. Guidance on monitoring and investigation of groundwater-dependent terrestrial ecosystems (GWDTE). Environment Agency of England and Wales report available at www.environment-agency.gov.uk.

[3] Whiteman, M., Skinner, A., Hulme, P. and Brooks, A., 2010. Determining significant damage to groundwater-dependent terrestrial ecosystems in England and Wales for use in implementation of the Water Framework Directive. Ecol. Eng. (2010), doi:10.1016/j.ecoleng.2010.03.013

Water Resources Assessment and Management of Low Productivity Aquifers at Scottish Water.

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Scottish Water produced and distributed 750,000 mega litres (Ml) of water in 2009/2010 to a population of 5.035 million. Of this, 26,500Ml is from groundwater sources equivalent to 3.6% and the rest from surface sources (Lochs, Reservoirs, Rivers/Buns). SW own and operate around 140 boreholes all over Scotland (with multiple wells at some sites) but in relation to regulatory counting of sources, with respect to water treatment works, the official count comes to 44 boreholes and 34 springs.

Some Scottish Water groundwater sources, particularly in the North of Scotland, exploit low yielding bedrock, raised beach and glacial aquifers.

SW develops robust engineering solutions through long term asset planning in assessing its asset capabilities and deficiencies, coupled with a Water Resources Plan and Supply Demand Balance assessment that gives a holistic view of capability to meet water supply needs and requirements for future capital investments.

Extensive hydro-geological investigations and modelling are carried out to determine the viability and sustainability of exploiting low yielding aquifers. Because these aquifers are often isolated and the only viable options, they are managed as stand-alone assets with its water resource plan and a supply demand balance. Drought contingency, drinking water safety and catchment management plans are developed to allow SW monitor and mitigate interruption to public water supply.

Groundwater Supplies in the Archean Aquifers of Aberdeen

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The shallow crystalline rocks of Aberdeenshire form a classic example of low-productivity, yet locally important, aquifers. Although there are no current public groundwater supplies in the region due to the frequently low yields available, almost every smallholding in the area has

been or is supplied by groundwater, mainly via springs or shallow wells sourced from these aquifers. When the Aberdeen Western Peripheral Route (AWPR) was formulated to address major traffic issues in the area, the designers soon realised that the many cuttings through the undulating hills would necessitate detailed and complex studies (intrusive site investigations, aquifer testing and numeric modelling) to clarify the potential effects of the cuttings on these many private water supplies (PWS). The results of the PWS numeric modelling are now being used to inform a series of dewatering licences which SEPA requires for each major cutting intersecting groundwater, another unprecedented aspect of the work.

This paper describes the data-gathering, conceptualisation, risk assessment and modelling of the numerous groundwater-based springs, wells and boreholes in the vicinity of the proposed AWPR. Twenty two aquifer tests were performed and numerous holes were drilled to characterise the local aquifers. An important finding from the study is that, even though the dominant flow is within fractures in the highly weathered bedrock zone, the fracturing within this zone is so dense that at a supply scale that the aquifer may be modelled using anisotropic but granular-type flow mechanisms. Interpreted transmissivities showed a remarkable variability, reflecting the depth and degree of weathering in the primariy granitic and gneissic bedrock.

Modelling the potential effects of each cutting on each PWS comprised conceptualising the recharge areas and flow movement and checking this conceptual model with basic catchment water balances. Where the conceptual plan was found to be robust, it was followed by construction of detailed MODFLOW-based numerical models. The conditions, limitations and assumptions made in the conceptual models led to some unusual approaches to the numerical modelling. Once constructed, these models were iteratively calibrated against measured field conditions. Numerous PWSs were evaluated in response to the predicted cuttings, and several supplies were judged to be at sufficient risk of reduced yield or quality to necessitate replacement, whilst the other supplies will be monitored during construction.

The Assessment of Groundwater 'Future Resource Value' and the Allocation of Groundwater Receptor Status

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The status of groundwater as a receptor in its own right was firmly established by the Groundwater Directive (GWD - 80/68/EEC). The transposition of GWD objectives, namely; the prevention of List I substance entry and the limiting of List II substance entry to avoid pollution, has led to a long established pattern of regulatory control and associated groundwater protection. The parallel but complimentary approach inherent within the Groundwater Daughter Directive (GDWDD – 2000/118/EC) maintains the 'Prevent and Limit' ethos and generally only varies the terminology adopted in line with Water Framework Directive requirements; namely the use of non-hazardous and hazardous substance descriptors. Neither the GWD nor GWDD affords much opportunity for a viable case to be made challenging the 'receptor' status of a body of groundwater within a prescribed geologic setting/formation. As such, an all encompassing approach to groundwater receptor status has long been adopted by the various UK Environment Agencies. The latter has been subject to both criticism and challenge; generally on the basis of the low yield potential and poor groundwater quality that can exist in many superficial and artificial deposits. A method is presented which, whilst aiming to redress the imbalance in regulatory approach that is perceived to exist, maintains both the 'pervasive' groundwater receptor status in relation to hazardous substances and the key pathway role for all groundwater systems. This method targets the assessment of pollution by non-hazardous substances within groundwater having 'future resource value'. The latter is assigned, for groundwater units falling outwith the designated boundaries of 'Groundwater Bodies', through demonstration that UK Technical Advisory Group (UK TAG) criteria is met. Conversely, those low yield systems falling short of the UK TAG criteria are not afforded receptor status and are protected solely in relation to their 'pathway' role. A tiered approach to this process has been 'recommended' in SEPA's recently issued guidance document (WAT-PS-10-01 Assigning Groundwater Assessment Criteria for Pollutant Inputs).