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ABSTRACTS AND PHOTOS FROM FIELD TRIP

Inferior Oolite Aquifer of the South Cotswolds: New Conceptual Understanding of Aquifer Recharge and the Development of a Numerical Model to Support Increased Abstraction for Stream Support

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The Great and Inferior Oolite aquifers beneath the Malmesbury Avon River Catchment in the South Cotswolds of England have been used for Public Water Supply (PWS) since early last century. Development of each aquifer for PWS continued through the century. In the 1970's Wessex Water Authority developed the Malmesbury Groundwater Scheme (MGS), which doubled the annual PWS take from the Great Oolite aquifer. Testing of the MGS identified that abstraction reduced flows in the River Avon. To mitigate this impact, augmentation boreholes were drilled to pump Inferior Oolite water (up to 7.5 ML/d) into the river to ensure prescribed flows were maintained.

This arrangement worked until the 1990 drought when flow in the River Avon reduced to just a trickle of water at Malmesbury. This identified the inadequacy of the current licence conditions to protect the river flow. Since 1995 increased rate of stream support from the Inferior Oolite aquifer have been used to maintain acceptable river flows.

This paper details the work undertaken to assess the sustainability of using the Inferior Oolite for stream support at higher rates (up to 27 ML/d). This has included construction of new observation boreholes, routine stream gauging, water quality monitoring and pumping trials. A 'signal' pumping trial was undertaken in 2003, when stream support abstraction rates were maximised to elicit responses in observation boreholes. The BGS were commissioned to develop a 3D model of the aquifer system, comprising the Great Oolite upper aquifer, the Fullers Earth aquitard, and the Inferior Oolite/Bridport Sand lower aquifer.

Analysis has identified that the stream support water is obtained from a largely hydraulically discrete compartment of Inferior Oolite. The boundaries to the compartment are formed by the outcrop edge and geological faults. The Inferior Oolite has a high hydraulic conductivity (K), but low storage compared to underlying Bridport Sand, which has a low K but high specific yield. These contrasting properties and the aquifer geometry, means the Bridport Sand acts as the 'reservoir' and the Inferior Oolite transmits the water to the abstraction points. Recharge to the Inferior Oolite is provided by leakage from the Bridport Sand and direct recharge over the outcrop area.

A numerical groundwater model has been constructed to verify this conceptual understanding. A number of technical issues with cell rewetting and stability had to be overcome. A well-calibrated model was achieved and this has been used to test the sustainability of increased abstraction and impact on protected rights.

These findings will be used to support a revised steam support abstraction licence application, which will ensure the long term integrity of the PWS sources and maintain acceptable river flow in the town of Malmesbury.

Investigation of stratigraphical influences on the limestone hydrogeology of the Wye Catchment, Derbyshire, UK.

Banks, V.J., Gunn, J. and Lowe, D.J.

Recent investigation of human impacts in the Wye (Derbyshire) Catchment has confirmed that published views of the local and regional hydrogeology may lack sophistication. Ongoing study of the results of dye-tracing, chemical analyses of groundwater and hydrograph analysis, alongside detailed considerations of speleogenetic processes, bedrock lithology, geological structure and terrain evaluation, has produced encouraging initial results. A more refined conceptual model is suggested, acknowledging differences in the hydrogeological behaviour of the distinct bedrock units and incorporating the effects of the underlying stratigraphical influences on the limestone hydrogeology of the area as a whole. A similar approach may assist the understanding the hydrogeology of other karstic aquifers.

Analysis of discharges from a large drainage adit, Carboniferous Limestone, Derbyshire, England

M Shepley, EA, Midlands

The flow hydrograph of a large mine drainage adit, the Meerbrook Sough, has been analysed in order to determine the large-scale hydraulic behaviour of the Carboniferous Limestone aquifer. A conceptual model has been constructed using available hydrological and hydrogeological data. The analysis shows that flow through the Carboniferous Limestone can be dominated by diffuse flow with the aquifer storage also important. The conceptual model of groundwater flow is supported by numerical modelling. The dominance of diffuse flow is attributed to the large-scale dewatering below the base level of drainage, which has deactivated a significant proportion of the conduit flow system. The source of the storage in the Carboniferous Limestone is discussed with reference to hydrogeological field data and historical and industrial archaeological sources on the mining in Derbyshire.

LOWLAND KARST HYDROGEOLOGY IN IRELAND. INVITED KEYNOTE SPEECH

David Drew Trinity College Dublin

Almost a half of the Republic of Ireland is underlain by Carboniferous limestone most of which is sufficiently pure to be karstified. Upland outcrops of limestone are largely confined to plateaux in the west and north west such as the Burren and Ben Bulben and much of the karstified limestone underlies the undulating lowland of central Ireland which rarely exceeds 100m in elevation. The lowland limestones are the principal source of groundwater in Ireland and also coincide with the most economically developed and intensively farmed areas – unlike the situation in Britain where most karst limestone areas are relatively peripheral uplands. Such limited hydrogeological investigations as have been undertaken of the lowland limestones of Ireland suggest that extensive karstic flow systems exist, that they are intimately related to surface drainage systems and that the groundwater and associated karst features are often highly vulnerable to anthropogenic influences.

Upper Dinantian (Burren) Limestone Aquifer.

E. Daly

The Upper Dinantian Limestone aquifer in the southeast central part of Ireland covers an area of about 1,250km2 and has an estimated average annual groundwater or baseflow throughput of the order of 6m3/s.

The aquifer contains many features typical of karst areas such as swallow holes, dry valleys, deep water tables and discharges through numerous large springs. However, the aquifer flow regime can be described in classical hydrogeological terms.

Instrumenting turloughs : problems and progress

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Turloughs are topographic depressions in karst that are intermittently inundated on an annual basis, mainly from groundwater, and have a substrate and/or ecological communities characteristic of wetlands. They are markedly smaller than poljes and most do not have the extensive flat floor and steep surrounding slopes that are characteristic features of poljes. The majority of turloughs are in the Irish Republic with only two turlough sites in the United Kingdom, The Fardrum and Roosky Turloughs which are located near Enniskillen in County Fermanagh, Northern Ireland and Pant y Llyn in south Wales. Both sites are on Carboniferous limestones, both are Special Areas of Conservation (SAC) under the European Union Habitats Directive and both have been under threat from limestone quarrying. In Northern Ireland the Environment & Heritage Service has commissioned research to clarify the hydrogeology of the area and the extent of quarrying impacts on the turloughs, and the Countryside Council for Wales have commissioned a similar project at Pant y Llyn. At the heart of both projects is an attempt to understand surface water - ground water interactions in the Carboniferous Limestone and this is being achieved by a combination of water tracing using fluorescent dyes and water balance studies. The latter commenced on 1st October 2005 and included measurement of rainfall, evaporation, allogenic inputs, water levels in the turloughs and the discharge of springs. Initial results from Fermanagh indicate that, although quarrying has ceased as a consequence of action by the Planning Service, the existing quarries continue to have a detrimental impact on turlough hydrology. It is planned that monitoring will continue for at least two years before a decision is taken on possible remedial action such as grouting of the quarry wall.

Regional Groundwater Circulation of the Caribbean Yucatan Aquifer Revealed Using Temperature and Specific Electrical Conductance Observations

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The Caribbean Yucatan aquifer is a density-stratified karstified coastal carbonate aquifer comprising a fresh water lens (FWL) overlying a saline water zone (SWZ). Cave diving exploration has revealed more than 500 km of flooded cave passage that extend from coastal springs through to at least a distance of 10 km inland. A regional dataset of fresh and saline water temperature and specific electrical conductance (SEC) has been compiled through surface and cave diving observations. The SEC of the FWL from 9 to 3.4 km inland increases very slowly with a gradient of 0.35 ± 0.14 mS/cm per kilometre from a low of 2.48 mS/cm at 8.67 km inland, however higher gradients of SEC increase occur closer to the coast (2.11 ± 0.31 mS/cm per kilometre, from 4 to 0.4 km) due to increased mixing with saline water. Whilst the SEC of the SWZ in conduits is spatially consistent (50.00 ± 1.25 mS/cm, n=20) reflecting the characteristics of the marine source water (50.55 ± 0.42, n=4), the temperature of the SWZ decreases from a high of 27 - 28 oC near the coast to ~25.5 oC at 20 km inland. It is therefore suggested that warm shallow Caribbean sea water is moving rapidly to at least 9 km inland though the conduit systems. This suggestion is supported by results from dye tracing and also flow data from oceanographic current meters. Our results suggest that in some coastal carbonate aquifers the conventional model that the fresh water outflow entrains a parallel coastward saline flow with compensatory saline inflow at depth, may not apply. Our results also suggest geothermal heating may not be the major drive for SWZ circulation as it is in other carbonate aquifers such as the Biscayne aquifer of Florida.

Slade Brook

Anna Wetherell, English Nature

There is a SSSI in the Forest of Dean, Slade Brook, recently notified for its actively forming tufa dams. The site came to the fore because a quarrying company wanted to extend its quarrying operations - would this activity, 2km away, have an impact on the potential SSSI? We needed to investigate whether the quarry (in Carboniferous Limestone) was at all linked to the site, and, if it was, what the likely impacts would be and if they could be mitigated against.

Dye tracing proved a direct link between the quarry and the SSSI, with significant inflow just above where the tufa dams start. The process of tufa formation is complex, as indeed are karst and cave systems such as illustrated here. We therefore concluded that there was potential for significant impacts on the SSSI. Mitigation thus far has consisted of extensive monitoring, with agreement on what will be done should the monitoring indicate problems. In addition, restoration of the quarry will include attempts to 'recreate' the epikarst, to try to ensure that recharge of the system maintains the necessary chemical composition.

In my paper I will be able to outline the research that was done, the results of the monitoring thus far, and initial indications of the progress of the quarry restoration. The initial stages of this work was written up in Earth Heritage - see link below.

http://home.btconnect.com/seaburysalmon/pdf/eh23f.pdf - article on page 8/9 "Protecting tufa with new techniques"

The principal controls on the development of permeability in these strata are the structure, stratigraphy/lithology and geomorphic history. The development of permeability along faults and related structures has a very important role in the movement of groundwater in this aquifer.

In recent years the exposure of parts of the aquifer in quarries and the results of geophysical surveys and trial well drilling has provided additional insights into the flow regime of this aquifer.

Combined approaches to the assessment of the impact of quarry dewatering impacts on limestone aquifers – a case study from South Wales

Mike Streetly, ESI

This case study presents the results of many years of monitoring and investigation at a site in South Wales. Two well established quarries have worked the Carboniferous Limestone for many years. The quarries are actively dewatered and water is discharged offsite into the surface water system. Concerns have been expressed about the potential impacts of the quarries on spring based supplies along strike. Tracer tests carried out by Bristol University clearly showed that the key spring was sourced from a series of sink holes to the south of the quarry. The surface water catchments of these springs were well delineated by the local topography. In order to establish the associated groundwater catchments, a soil moisture balance model was developed for the area and combined with a simple 1D model of the limestone system to generate synthetic hydrographs for the spring flow. This was compared to the measured flow at the spring and used to confirm the combined groundwater & surface water catchment of the spring. A similar approach was used to assess the current catchment area of the quarries. This approach provided a robust demonstration of the transient water balance of the whole block of limestone and helped to demonstrate the absence of current impacts.

Long-term impacts of sub-water table quarrying on the hydrogeology of a karstified Carboniferous Limestone aquifer: A case study from the Mendip Hills, England.

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Large-scale quarrying of limestone can impact on local and regional hydrogeology, affecting both surface and groundwater systems. In the Mendip Hills, SW England, extraction of the Carboniferous Limestone has been focussed in the scenically less valuable eastern Mendip, with deep sub-water table working to maximise reserves. This paper focuses on the long-term hydrogeological impact of sub-water table quarrying and progressive dewatering of the Carboniferous Limestone around Torr Quarry.

Dewatering impacts both groundwater storage, which is dominantly within the diffuse flow zone, and groundwater flow, which also occurs within a well-developed conduit network. Repeat dye traces have been undertaken from a series of sinking streams at various stages of dewatering, and compared with detailed records of groundwater-level and spring discharge. Over a 20 year period dewatering has created a zone of water table depression around the quarry, with sump water levels currently maintained some 30 m below pre-dewatering levels. The development of the zone of depression reflects the heterogeneous and anisotropic nature of limestone, and the history of pumping. The sump is sourced both from diffuse seepage and leakage from conduits. Tracer results demonstrate progressive loss of water from phreatic conduits with expansion of the zone of water table depression. There has been considerable derogation of flow to local springs, which now only discharge during periods of significant recharge. Although the quarry void has not intersected any large conduits, the expansion of the zone of water table depression has progressively modified conduit behaviour in the surrounding aquifer. Leakage of water from the conduits into the diffuse zone prevents flow over phreatic loop tops, except during significant recharge. Dye tracing provides a valuable tool to complement conventional techniques for monitoring the impact of dewatering in karst aquifers.

Defining aquifer-scale hydrogeological criteria for karst aquifers

Steve Worthington, Worthington Groundwater

The identification of an appropriate conceptual model for limestone aquifers is often challenging because of the uncertain effects of dissolution. Equivalent to porous medium (EPM) approximations are often chosen because it is usually unclear how the effects of karstification might be manifested at an aquifer scale or how such effects might be incorporated into numerical models.

Extensive cave mapping, tracer testing, and spring monitoring in the British Carboniferous Limestone have shown that flow is convergent to conduits, which terminate in a downgradient direction at springs. This implies a concave-up water table, and the catchment areas (or capture zones) for springs have sometimes been called groundwater basins to reflect this concavity. British Carboniferous Limestone aquifers lack sufficient water-level data from boreholes to demonstrate this well. However, the Carboniferous Limestone aquifer at Mammoth Cave, Kentucky, has copious data that demonstrate this and make it an ideal place to investigate differences between EPM and karst aquifers.

Two numerical simulation of flow in the Mammoth Cave aquifer were performed using the popular MODFLOW code; the first assumed it behaves as an EPM and the second assumed it is karstic and thus has conduits discharging to springs. The karstic realisation provided a better fit to heads, a much better representation of spring discharge, and accurate representation of convergent flow to springs for 58 tracer tests from wells, dolines, or sinking streams. The Mammoth Cave aquifer exhibits a number of key aquifer-scale characteristics that differ from EPM aquifers: tributary flow to springs, troughs in the water table, a decrease

in hydraulic gradient and increase in hydraulic conductivity (*K*) in a downgradient direction, substantial scaling effects in *K*, and a decrease in *K* with depth below the water table. Investigation of other karst aquifers has shown that these characteristics are common.

British limestone aquifers younger than the Carboniferous often have a greater density of boreholes than the Carboniferous Limestone. Consequently, the above criteria developed at Mammoth Cave could be used to help address the controversial question of whether their behaviour is closer to karst or to EPM aquifer end members.

POSTERS

The GIS approach to karst in the UK

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Karstic aquifers are widespread throughout the British Isles and are not just confined to the classic Carboniferous Limestone karst. An essential pre-requisite for any hydrogeological investigation of the Carboniferous Limestone and other karstic aquifers is the identification of features such as stream sinks, springs, sinkholes and caves. To this end, the British Geological Survey is creating a national database and GIS of such features, which includes the Carboniferous Limestone but also extends to other karstic rocks such as the Chalk and particularly the Permian and Triassic gypsum and Triassic salt where rapid active dissolution has caused significant subsidence and building damage.

In addition to the identification of specific karst features, the British Geological Survey has created a national karst geohazard GIS. This has been created by identifying all the soluble lithologies and extracting them from the 1:50,000 scale digital geological map. Each soluble lithology has been given a rating depending on the nature and occurrence of dissolution features, based on factors including lithology, topography, geomorphic position and superficial cover deposits. This national zonation of the soluble rocks can be used to identify areas where karstic groundwater flow is significant and where dissolution features may affect the stability of linear routes such as roads and pipelines. Both datasets are applicable for site investigation, groundwater investigations, planning, construction and the insurance businesses.

Keywords: Carboniferous Limestone; dissolution; karst; subsidence; GIS

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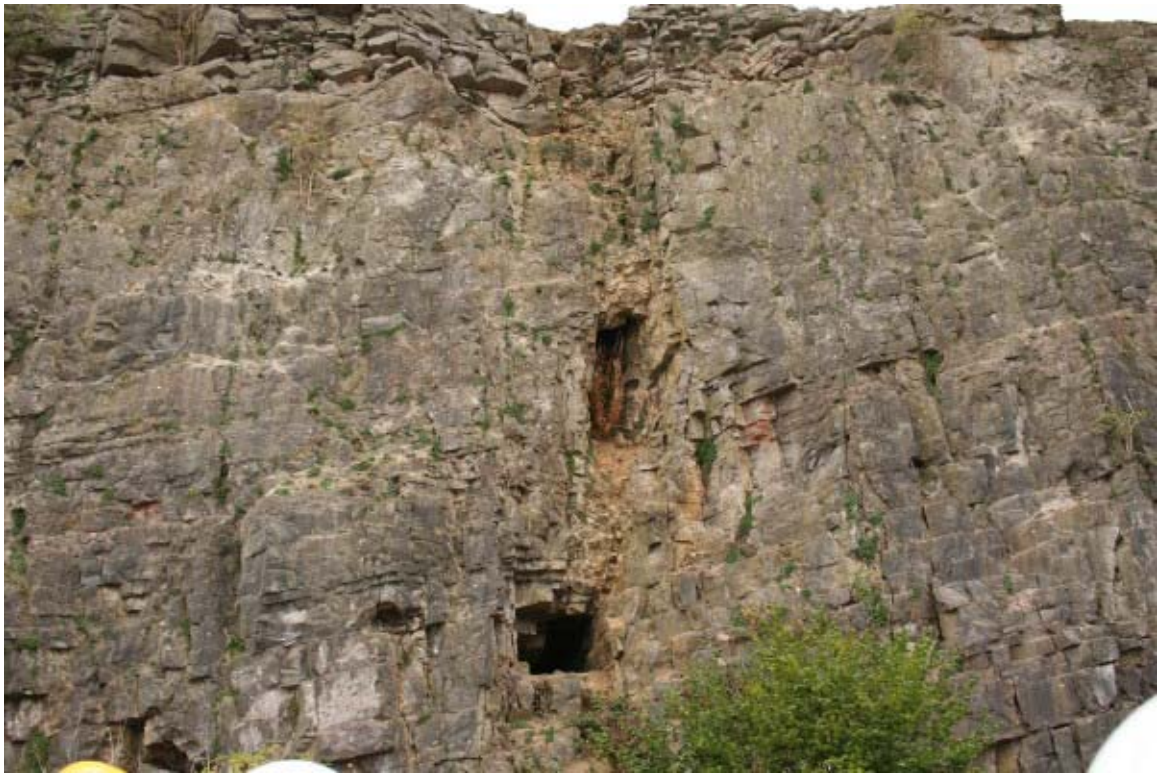
Pete Smart in full flow

Lectures on Day 1

Cloford Quarry

Tor Quarry



Caves formed in Neptunian dykes

Palaeo surfaces

Neptunian dyke

Iron staining from Triassic deposits