Abstracts Groundwater Tracers and Quantitative Hydrogeology (incorporating the 2009 Darcy Lecture)

Morning session – Artificial Tracers

Investigating attenuation and flowpath characteristics using artificial tracers

Louise Maurice (British Geological Survey)

Natural gradient artificial tracer tests are a useful tool for determining groundwater catchment areas but also provide valuable information on the nature of groundwater flowpaths and the degree of attenuation that occurs in the aquifer. Recent tracer studies in the Chalk illustrate how tracer testing can show both the degree to which attenuation occurs along groundwater flowpaths and the type of attenuation mechanism that is occurring. Hundreds of sinking streams recharge the Chalk aquifer, and the few previous studies suggested that flowpaths fed by Chalk stream sinks have rapid flow and low attenuation. However, results of recent tracer tests indicate that rapid groundwater flow can be combined with high attenuation, and that the major cause of attenuation is likely to be hydrodynamic dispersion via flowpath branching. New DNA tracer technology may provide a new means of investigating flowpaths with high attenuation because the DNA tracers can be injected at high concentrations.

Tracing the Occurrence of Catchment-Scale Karst in the Hertfordshire Chalk Using Bacteriophage

Simon Cook, Ciara Fitzpatrick, William Burgess (University College London)

The occurrence of karst in the Hertfordshire Chalk aquifer, along the Palaeocene feather edge on the northern limb of the London Basin, was established through a series of tracer tests by the Metropolitan Water Board in the 1920's and 1930's (Harold, 1937). These tests indicated karstic groundwater flow connections over distances of >15 km with flow velocities of 1-4 km/day. Recent point source contamination of the aquifer has prompted a reinvestigation of the karst system which appears to be responsible for increasing the rate and extent of contaminant movement a distance of 20km from its source.

To address uncertainty regarding the spatial distribution of karst flows, and to enable derivation of hydrodynamic transport parameters, a new suite of tracer tests has been conducted. Three species of bacteriophage, biological tracers, were introduced into the aquifer at key locations, via (1) a major swallow hole cluster, (2) an observation borehole on the margins of the observed surface karst, and (3) an observation borehole close to the contaminant source.
Tracer breakthroughs determined by sampling at 23 locations including public supply wells, springs and observation boreholes indicate that karstification is more widespread than indicated by previous testing, and karst flows occur across the full extent of the contaminated aquifer.

Groundwater flow velocities of 0.4-3.9 km/day suggest a relationship between tracer attenuation and distance from the Palaeocene feather edge, contributing to a new conceptual understanding of the Hertfordshire Chalk karst consistent with the model of Maurice et al (2006).

Tracer breakthrough observations have been analysed using single and dual-porosity analytical models in order to parameterize a distributed groundwater flow model incorporating the karstic features. The tracer observations are successfully reproduced within this regional groundwater model.

References

Harold, C. 1937, *Thirty-second Annual Report on the Results of the Chemical and Bacteriological Examination of the London Waters for the Twelve Months ended 31st December 1937*, Technical report, Metropolitan Water Board, London.

Maurice, L., Atkinson, T., Barker, J., Bloomfield, J., Farrant, A. and Williams, A. 2006, *Karstic Behaviour of Groundwater in the English Chalk*, Journal of Hydrology, Vol. 330, p. 63-70.

Laboratory and Field Experiments on the Movement of Viruses In Sandstone Groundwaters

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Evidence from analysis of abstraction well and piezometer samples suggests that viable human viruses can, surprisingly, penetrate to depths of at least several tens of metres in the groundwaters of the Permo-Triassic Sandstone aquifers of the UK. To investigate the processes involved, laboratory and field experiments have been undertaken. Experiments at *in situ* temperatures, ionic strengths, and groundwater velocities on sandstone cores of up to 24 cm in length show that various bacteriophages and poliovirus are strongly attenuated during passage through matrix pore space: phages and poliovirus appear to behave similarly. Synthetic silica colloids, representing the dominant composition in the sandstone groundwater colloid population, are also strongly attenuated over similar distances. However, when the colloids and viruses are injected together, the virus recovery as measured in total plaque forming units rises above that injected, implying release of virus particles attached to the rock during previous experiments. The results of a forced-gradient field experiment over a saturated depth of 35 m, with monitoring at six vertical intervals, show that bacteriophage are indeed very mobile in all sections of the sequence over a horizontal distance of 7 m. Although interpretation is still in progress, it would appear that virus mobility can be considerable over at least limited distances, even in the absence of fracture flow, and that the presence of other colloids plays an important role in enhancing this mobility.

A combined groundwater tracer test and age-dating experiment using SF6 and CFCs in a fissured, karstic aquifer – advances in understanding regional flow and solute transport in the Yorkshire Corallian.

Aidan Foley, Tim Atkinson (University College London)

A series of tracer experiments conducted in the Corallian limestone of Yorkshire, between 1995 and 2004, culminated in an experiment combining sulphur hexafluoride (SF6) as an artificial tracer with the model groundwater age dating capacities of chlorofluorocarbons (CFCs) 11 and 12. The analytical technique used permitted simultaneous measurement of the injected SF6 and the ambient CFC tracers. SF6 tracer breakthrough curves enabled characterisation of tracer arrival times throughout the aquifer and definition of extended solute tailing at public water supply wells and observation boreholes. CFC data permitted comparison of measured groundwater velocities with simple model groundwater ages and thereby the calculation of degrees of mixing of different end-member waters within the aquifer. Results are supported with data gathered from the previous tracer experiments, major ion analyses, pumping tests, and tritium data obtained in the 1960s. The data are used to support a qualitative conceptual model of the role of fissures and karstic voids in flow and solute transport on a regional scale within the Corallian, together with a semi-quantitative network model of localised karst conduits within the aquifer. The findings have implications for existing source protection zones and the management of public water supplies.

The architecture of recharge in unsaturated fractured rock

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Tracers are a common technique in karst hydrogeology, but relatively rarely used to track flow or residence time in the unsaturated zone. We have carried out artificial tracer tests from the ground surface to underground sites at depths down to 100 m in caves in Gibraltar, the Mendip Hills and NW Yorkshire. We have also monitored stable isotope ratios in rainfall, soil water and cave waters, providing a natural counterpart to the artificial tracer experiments.
The artificial tracer results show that recharge from a point source undergoes marked lateral migration during downwards percolation through the unsaturated zone. In general, tracer from a single injection point on the surface emerges at more than one inlet in the cave beneath, with a lateral spreading that appears to be controlled by local geological structure. In steeply dipping lime-stones (Gibraltar, Mendip Hills) tracers migrate down-dip as well as vertically and along strike.

Detailed residence time distributions were obtained by monitoring tracer concentrations at selected sites in the British caves. Tracer storage occurs on timescales of a few days, ten of days and hundreds of days, though not all occur at every site. The British sites showed rapid initial breakthrough followed by storage over tens and hundreds of days, whereas breakthrough took several weeks in Gibraltar. Sites with ten- and hundred-day residence times showed exponentially decreasing values of tracer concentration, indicating storage in a well-mixed reservoir.

Isotope tracers also showed patterns compatible with a well-mixed reservoir. Mean residence times estimated from isotopes are closely comparable to those found from artificial tracers. The input of isotopic tracers is distributed in both space and time, whereas artificial tracer inputs are concentrated in both, so the similarity of results suggests that mixing is a continuous and spatially homogenous process. Lateral dispersion is likely to reflect the structure of fracture networks whereas temporal mixing is probably due to the variations in apertures from one fracture to another. Simple network models have been used to explore these ideas.

Afternoon session – Natural Tracers

Chalk catchment transit time: unresolved issues

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The mean transit time (MTT) of a catchment can be defined as the average residence time of water from the point of rainfall reaching the land surface to river outflow at the foot of the catchment. MTT is thus a combination of surface runoff and baseflow. A reliable estimate of MTT is desirable not only because it is a function of storage and flow pathways, but also because it has implications for water quality. Previous studies worldwide have shown that MTTs rarely exceed 20 years even for very large river systems, but the Chalk is a unique type of aquifer for which no estimates of catchment MTT appear to exist. In the case of the Lambourn catchment of the Berkshire Downs, monitoring data for tritium in the river during the 1970s and 1980s suggests an MTT of ~15 years, i.e. comparable to other river basins. However, the generally assumed Chalk infiltration rate of ~1 m/yr based on a number of different studies would indicate a mean delay of 50 years attributable to the unsaturated zone alone, given that its thickness averages ~50 m in the Lambourn catchment. A further delay averaging a decade or more according to SF_6 dating would then be imposed by travel through the saturated zone towards discharge in the river, implying a very long MTT as the River Lambourn consists almost entirely of baseflow. Even allowing for the existence of a degree of bypass flow, the contrast between the apparent and calculated MTTs challenges our present understanding of the hydrological functioning of the Chalk.

Sulfate stable isotopes as indigenous tracers of solute sources in groundwaters.

Simon Bottrell (University of Leeds)

The sulfate molecule contains atoms of two elements that exhibit readily measurable natural variation in their stable isotope composition. These isotopic compositions are often characteristic of different sulfate sources and are resistant to change at the near-neutral pH and relatively oxidizing conditions of many groundwaters. Thus sulfate isotopic compositions can act as reliable tracers of sulfate source in groundwaters on time-scales of thousands of years.

This talk uses two recent studies on the Triassic Sherwood sandstone aquifer to highlight the utility of sulfate stable isotopes as a “forensic” tracer of sulfate and solute sources in groundwater. In the first, the isotopic composition of sulfate associated with a saline component affecting supply wells in the Selby wellfield (Yorkshire, UK) was able to distinguish between the several possible geological sources of saline water. In the second, the contributions of multiple sources of sulfate to an urban aquifer (Birmingham, UK) were studied. Unfortunately the sulfate

isotopic compositions of made-ground and sewage-derived sulfate were found to be similar and (some combination of) these sources are a major contributor to solutes in the city centre area. However, in other parts of the aquifer the different natural and anthropogenic sulfate sources could all be distinguished and their contributions to the aquifer sulfate budget calculated. In particular, sulfate derived from oxidation of pyrite in Quaternary Drift deposits has characteristically ^{34}S- and ^{18}O-depleted isotopic compositions and the contribution from this source increases markedly in younger groundwaters as a result of drawdown induced by abstraction from the aquifer.

2009 Darcy Lecture
Environmental Tracers in Modern Hydrogeology: Reducing Uncertainty in Ground Water Flow Estimation

Peter G Cook (CSIRO Land and Water)

Environmental tracers can reduce uncertainty of hydrogeological predictions in all environments, but are particularly valuable in highly heterogeneous systems, where spatial variations in aquifer hydraulic conductivity may range over several orders of magnitude, and so hydraulic approaches are inherently uncertain. Despite the rapid growth of environmental tracers during the past few decades and their adoption by the research community, they are not widely used in routine hydrogeological assessments. This lecture illustrates the potential of environmental tracers through illustration using field sites in North America and Australia, and discusses methods for bridging the gap between research and practice.

Quantitative hydrogeology is often traced back to Darcy who, in the mid-19th century, observed a linear relationship between flow rate and hydraulic gradient, the proportionality constant later becoming known as hydraulic conductivity. Even today, ground water flow rates are most frequently determined as the product of measured hydraulic gradients and hydraulic conductivities, the latter determined using pumping tests. Although the last 150 years have seen considerable improvement in interpretation of pumping tests, and understanding of isotropy and heterogeneity, estimation of aquifer hydraulic conductivity values at appropriate scales remains a significant source of uncertainty. Within the past few decades, however, environmental tracer methods have been developed that can provide independent estimates of ground water flow rates, which have helped to overcome some of the problems associated with hydraulic approaches, particularly in heterogeneous systems. However, despite the ability of environmental tracers to constrain conceptual models of ground water systems and significantly reduce uncertainties in prediction, the methods are underrepresented in hydrogeological textbooks and are still not widely used for hydrogeological assessment.

There are a large number of environmental tracers, all with different properties and hence different potential uses. While environmental tracers that readily undergo chemical reactions can sometimes be used to determine reaction pathways, tracers that behave more conservatively may yield information on transport processes. Calculation of ground water residence times is one of the more common applications. Tracers that can be used for this purpose include radioactive isotopes, which decay at a known rate (e.g., ^{14}C, ^{3}H), tracers that are produced and accumulate in the subsurface (e.g., He), and tracers that are neither produced nor consumed in the subsurface, but have a variable and well-known input history (e.g., CFCs, SF_6). Ground water residence times in unconfined aquifers can be used to infer aquifer recharge rates, whereas in confined aquifers they allow quantification of horizontal flow velocities. Tracers present in much higher concentrations in ground water than in surface water have great potential for quantifying ground water discharge to surface water. In particular, dissolved gas tracers such as radon and helium will rapidly volatilise from surface water and so provide important tracers of recent ground water inflow. Radon (with a half-life of 3.8 days), in particular, can be used in quantifying rates of ground water discharge to streams, wetlands, and to the ocean, and also to determine the rate of water exchange between a river and its underlying hyporheic zone.