Temporal trends in the hydrochemistry and sewage-related microbiology – the results of multilevel sampling in the Nottingham sandstone aquifer

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Recent depth-specific monitoring of groundwater quality in multilevel piezometers in the Triassic Sandstone underlying the city of Nottingham, UK, showed that these urban aquifers are contaminated primarily by sewage and atmospheric sources. However, the temporal characteristics of the microbial and inorganic (e.g. nitrate, sulphate) contamination over a 20 month sampling period differ significantly reflecting the contrasting transport characteristics of surface-loaded solutes and particulate microbial species (bacteria and viruses) in Triassic sandstone. The differences are related to die-off rates of microbiological entities, preferential pathways and abandoned boreholes providing a rapid route for microbiological contamination to depth, transport mechanisms in the aquifer such as size-exclusion effects and finally differences in source loading characteristics of sewer leakage.

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Natural variations in the Baseline chemistry of UK aquifers: Contrasting hydrochemical signatures in Permo-Triassic Sandstones

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The extent of groundwater pollution and the impact of anthropogenic inputs to aquifers are difficult to quantify because of large natural variations in the environment. A knowledge of the baseline quality is essential for determining pollution and assessing the degree to which remediation is feasible. Baseline is defined as the range in concentration of an element or chemical substance in solution, derived naturally from geological, biological, or atmospheric sources. A multi-tool approach is used to determine the baseline in three contrasting regions of the Permo-Triassic Sherwood Sandstone aquifer. Regional variations are controlled by hydrogeological factors, sedimentary facies, mineralogy and residence time. Baseline concentrations of some elements (e.g. As, Ba and U) may breach drinking water standards by entirely natural processes.

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Pollution of Groundwater by Arsenic in Sedimentary Aquifers

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Reduction of iron oxyhydroxides (FeOOH), and its sorbed load of AS(V), pollutes groundwater in Hungary, Taiwan, the Bengal Basin, and Vietnam. In these areas, the process leads to extreme pollution (As > 1 mg/L) because it is driven by subsurface peat deposits, which are documented in Vietnam and the Bengal Basin. A model is given whereby fermentation of buried peat provides small organic moities (amines, sugars, carboxylic acids) that are carried downwards into the aquifer to drive reduction of FeOOH and arsenate. This model accounts for the vertical and lateral variation in arsenic pollution and its correlation to some degree with the distribution of known peat basins in the Bengal Basin and Vietnam. The effects of urbanization and unsewered sanitation can confuse interpretation of natural groundwater compositions and contribute to the lateral patchiness of arsenic distributions. Dissolved ammonium in aquifers is contributed by the microbial fermentation of buried peat deposits, so ammonium is not an infallible indicator of faecal contamination of groundwater in tropical deltaic settings. Simple redox stoichiometry shows that arsenic pollution at concentrations of tens of microgrammes per litre may arise from pyrite oxidation in sedimentary aquifers but this does not occur in the areas considered. Arsenic pollution by competitive exchange with phosphorus (from any source) or bicarbonate is a process not naturally important, but it may operate where anthropogenic influences disturb local environments.

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Analysing step-drawdown test in heterogeneous aquifers

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The methods commonly applied for analysing step-drawdown test data have all assumed that the aquifer is homogeneous while the aquifers, particularly consolidated aquifers, are usually heterogeneous. A new method is introduced to analyse step-drawdown test data for both homogeneous and heterogeneous aquifers. This method is based on homogenising variable discharge pumping tests and can be applied to confined, leaky, and unconfined aquifers. After homogenising the pumping test data, based on an obvious logic, aquifer losses and well losses are separated. Therefore the proposed method directly calculates the well loss in the pumping well and it does not need to use the equations and coefficients of the Jacob (1947) and Rorabaugh (1953) methods.

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ConSim, MT3D and reality

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Analytical risk models are now firmly established as tools for predicting likely contaminant impacts from contaminated land and landfills on groundwater receptors. These risk models are generally used in consultancy for lower tiered analyses or as screening tools to prioritise sites. ConSim is an Environment Agency probabilistic risk model, which simulates unsaturated and saturated zone transport and can predict contaminant concentrations and travel times to receptors. To test the ability of this analytical risk model to accurately predict likely concentrations at receptors a comparison has been made between a large established data set, a detailed numerical flow and transport model and ConSim. The probabilistic results from ConSim contained the deterministic most likely results from the numerical model and the actual field data. Following a statistical analysis of parameter sensitivity for both models the source flux was identified as the key influential input. This study adds confidence to the results achievable from analytical probabilistic models both in terms of outputs and sensitivity. Additional enhancements to ConSim are planned over the next 12 months and these will be discussed in the light of findings from this exercise.

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Groundwater – Surface water interactions: Birmingham aquifer and the River Tame

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We report on groundwater – surface water flow interaction data collected as part of a wider study to assess contaminant fluxes from urban contaminated land to surface water receptors. The field study is based on the 7-km reach of the River Tame that crosses the Birmingham unconfined Triassic sandstone aquifer. Baseflow is estimated to increase river flow over this reach by around 20%. Field data indicates flow adjacent to the river occurs through both the aquifer and the overlying alluvial material before discharging through the bank as a seepage face and across the river bed typical comprising ~ 2 m thickness of sands and gravels.

Continuous monitoring of head data has recorded the influence of river flood events on groundwater levels in adjacent river-bank piezometers and localised flow reversals occur. These localised groundwater level fluctuations are governed by flow within the capillary fringe and the overlying unsaturated zone driven by rapid head changes in the adjacent river. Estimates of storage from this data are several orders of magnitude lower than expected for unsaturated specific yields in sandy material. Analytical and numerical modelling is used to investigate steady state and transient flow in the saturated and unsaturated zone adjacent to the river.

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Groundwater Droughts and the Impact of Climate Change

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The concept of a drought is generally applied to "rainfall droughts", considering the consequences to agriculture and gardens, and "hydrological droughts", along with the consequences to river flows and water resources. Less research work has been carried out on the nature of a "Groundwater drought", although groundwater provides part or most of the resource for supply, along with the drought baseflow to rivers, for around half of the UK.

This paper considers the nature of the groundwater drought and the critical controls upon it. Various methods are presented for quantifying groundwater droughts using groundwater level and yield data from observation boreholes and supply boreholes. The paper also presents various approaches to assessing the potential impacts of climate change on groundwater droughts and provides results from investigations at a regional and national level.

This paper is based on the findings from the recent UKWIR project completed by WS Atkins and BGS on "Critical period groundwater yield" and summarises recent research with Southern Region of the Environment Agency on methods for assessing the impacts of climate change on groundwater resources.

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Changes in the Physicochemical Properties of Chlorinated Solvents following their Exposure to UK Aquifer Materials

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Chlorinated solvents (CHS) are amongst the most common and insidious of groundwater contaminants. The entry of such solvents into water saturated, fractured/porous media is critically dependant upon fracture aperture/pore size, interfacial tension (IFT) and wettability. Crucially, both the latter parameters can be affected by solvent composition and the chemical reactions that an invading solvent undergoes on its passage through the subsurface, and this has been investigated in a series of studies over the last three years.

Significantly the results demonstrate that aquifers may become solvent wetting following invasion, IFT values evolve during percolation through the subsurface and the mobilisation of various aquifer components and previous contamination can have an impact on both parameters. Not only do these finding have implications for the movement and fate of these chemicals in the subsurface but also for their subsequent remediation.

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Control on sorption by organic matter geochemistry

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A control on the attenuation of organic contaminants dissolved in groundwater is their sorption onto solid organic matter (OM) in the rock. Sorption modelling is usually based on the amount of OM, disregarding the impact of the type of OM. Organic carbon normalised distribution coefficients measured on seven samples (Lincolnshire Limestone, Glacial Till from Norfolk

and unconsolidated deposits) had a wide range (K_{OC} from 7.85 l/g to 767 l/g at 0.01 g/l trichloroethene), indicating variations with type of OM. The major element composition of OM isolated from these samples had H/O content correlating with measured K_{OC} values. A pyrolysis technique applied to whole rock samples was found to correlate with the elemental analysis, potentially providing more accessible composition analysis.

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Conceptualisation of flow patterns in a heavily exploited urban sandstone aquifer; Nottingham, UK

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As a step towards assessing the importance of the use of urban groundwater as a resource, and the impact of contamination, a conceptual and numerical model of groundwater flow in a large UK city (Nottingham) was constructed. The study incorporated first a detailed assessment of the long-term exploitation of the layered dual Formation Sherwood Sandstone aquifer. Water balance investigations demonstrated that changes in the contribution of urban recharge sources, to some extent, offset recent reductions in abstraction. Conceptualisation of model boundaries was facilitated using maps and cross sections constructed from borehole logs, and the southern extent of the aquifer was better defined. We constructed a numerical flow model, which was calibrated by trial and error to satisfactorily match observed heads and surface flows. Particle tracking was used to further the understanding of contamination patterns within the aquifer. The study revealed that during recent times the aquifer has behaved as a series of small catchments that can, and should, be considered independently. The simulations provide a general framework for the determination of management strategies and pollution patterns in future studies assessing the impact of urbanisation on quality of groundwaters in Nottingham.

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Modelling conduit spring flow using pipe-like conduits

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In general karst aquifer systems are very complex to simulate because they are characterised by a heterogeneous, discontinuous porosity and large spatial variability of hydraulic parameters such as hydraulic conductivity and storage coefficient.

A physically based model was tested for the first time to generate conduit spring hydrographs by simulating hypothetical catchment (800´800 m^2), with different configurations of conduit networks.

The results demonstrate the effect of using different configurations of pipe networks on spring flow hydrographs. This analysis has been used to inform the application of the model to a full-scale groundwater system.

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Characterisation of fluid flow through the unsaturated zone of layered aquifers using geophysical methods and sedimentary analogues

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A knowledge of the permeability distribution within the unsaturated zone is required to improve models of vadose zone flow in the Sherwood Sandstone. This can be achieved by identification of depositional processes using modern analogues, such as the Platte River, combined with observations in quarry exposures and identification of structures using Ground Penetrating Radar (GPR). GPR and Time Domain Reflectometry are also capable of monitoring moisture flow through the unsaturated zone, which allows the permeability distribution to be inferred.

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Poster:

Recharge Through the Drift

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UK aquifers have widespread Drift cover, which can significantly influence recharge, particularly where dominated by low-permeability lithologies. This ongoing study aims to characterise the major Drift domains, improving our understanding of recharge mechanisms, volumes and residence times. The initial work has focussed on examining the recharge characteristics of the extensive Till sheet of East Anglia, which is characterised by a thick sequence of low-permeability deposits overlying the Chalk aquifer. Two boreholes were drilled in Suffolk in November 2000, one angled at 45º. We are using the results of inorganic chemistry and stable isotope analyses of the porewaters, gas analyses, water level measurements and rainfall data to evaluate recharge through the Till. The preliminary results challenge some common assumptions.

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Diffusive exchange in the Chalk unsaturated zone: a comparative tracer test

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Unsaturated transport in the Chalk is said to be influenced by diffusive exchange between bypass-flow in the fractures and slow piston-flow displacement in the matrix. A comparative tracer test is planned on the Middle Chalk in Cambridgeshire to analyze the conditions that trigger fracture flow and diffusion between fractures and matrix. The experiment runs under natural rainfall conditions on a big grass-covered lysimeter and the tracers used are bromide and deuterium oxide. Because of the differences in the diffusion coefficients, the comparison

of the breakthrough curves will give information about the diffusive exchange mechanism. The data will be used in a modelling approach to assess the vulnerability of the Chalk aquifer to surface-derived pollution.

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The effect of moisture content on gas permeability of unsaturated sandstone

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Laboratory measurements have been used to assess the effect of moisture content on gas permeability of unsaturated sandstones. This work has relevance for VOC transport in the unsaturated zone.

A range of lithologies from the Permo-Triassic Sandstone were selected and their drainage characteristics and permeability were evaluated as a function of pore size distribution. The moisture content – gas permeability relationship was determined; it was postulated that at a critical moisture content the gas permeability may be drastically reduced. Moisture content was varied by centrifuging at selected speeds. After each test the sample was weighed and gas permeability measured.

Seasonal variations in moisture content may make parts of the unsaturated zone effectively impermeable to vapour at certain times of the year.

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Modelling of recharge in the lower unsaturated zone of the Chalk aquifer

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Detailed recharge models have been developed based on processes occurring in the soil zone; however, these models usually do not reproduce the time delay and damping occurring in the lower unsaturated zone. In the Chalk, the unsaturated zone can reach considerable thicknesses, producing significant time delays which must be included in recharge modelling if seasonal variations in water level are to be considered. Multiple flow pathways also require representation. In this work, we present a simple model of unsaturated zone processes for use in recharge modelling. A preliminary step in this modelling is the time series analysis of rainfall/water level response based on six-hourly records. The results of such a time series analysis, based on records at Deep Dean, Eastbourne, will be presented in this poster.

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Investigating the potential impacts of climate change on UK groundwater

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The potential impacts of climate change on groundwater in the UK are still unclear. As well as continuing uncertainty in estimating future climatic changes, one the major hydrogeological issues is uncertainty in predicting aquifer responses to climate changes. Simple models, developed and run using widely available historical data and synthetic future climatic scenarios based on accepted climatic simulations, provide a flexible approach to investigating the sensitivity of hydrogeological systems to potential climatic changes, and thereby reducing the hydrogeological uncertainty. During this project we are using a range of simple models of different aspects of idealised systems to investigate generic responses to changing climatic and hydrogeological parameters. The results will be analysed to indicate which parameters and processes could be expected to dominate under given conditions.

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The London-Dhaka Arsenic in Groundwater Programme

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The London-Dhaka Arsenic in Groundwater Programme addresses fundamental aspects of arsenic occurrence in the Bengal Basin. We have established:

1) The mechanism and hydrochemical conditions of As release to groundwater

2) At five sites:

spatial distributions of As over 15 km^2

depth distributions to 225 m

sedimentological associations of As-enriched groundwater

3) Groundwater ?^{2}H and ?^{18}O profiles to 225 at two sites

4) Indications of As variation with time.

These data have led to: a conceptual model of As in the aquifer; numerical models of As movement to tubewells; and a framework for safe groundwater development, and monitoring. Work continues on: sorption mechanisms (critical to predictions of As movement) and predictive modelling.

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Deconstructing adsorption variability:

The prediction of spatial uncertainty in pollutant movement

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The adsorption of organic pollutants onto soil is mainly dependant on the nature and amount of organic matter contained within the soil. Reported organic matter-normalised adsorption coefficients (K_{OC}) can vary by 6 orders of magnitude between study sites and by an order of magnitude within a site. Adsorption variability can therefore greatly affect the risk assessment of a given contaminated site.

The project is undertaking to better understand the controls on adsorption variability and identify physical-chemical properties of soil that can be used as markers to predict adsorption variability. Both the sorbent and sorbate affect adsorption and so our understanding of adsorption needs to be 2-dimensional. Quantitative Structural Activity Relationships (QSAR's) will allow us to link structural parameters of the pollutant to the properties of the soil.

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Coupled hydro-mechanical modelling of flow in fractured rock.

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Flow pathways through waste repository host rocks will be subjected to alterations due to changes in the stress distributions in the rock arising from thermal and mechanical processes. To understand the need to model the impacts of such changes for the performance assessment of a repository, a programme of work has been initiated under DECOVALEX III, an international collaborative research programme. The work is being carried out through a benchmarking exercise (BMT 2), in which data on rock characteristics for a specified repository setting are provided to several research teams. The poster presents the new modelling strategy, in which the hydro-mechanical (HM)-coupling will be performed only with the THM code UDEC.

Borehole optimization system

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The over-use of rural groundwater has led to environmental problems with rivers experiencing frequent low flows. Conversely, urban groundwater is a largely under-used resource, which has led to basement and tunnel flooding and geotechnical problems. The perceived risks of pollution have, until now, made urban groundwater unpopular with water companies, while British industry seems to have been unaware of the plentiful supplies of cheap groundwater since the 1960s. The Borehole Optimisation System (BOS) management tool has been developed to predict the quality at potential new boreholes. This will help to identify the best

use for urban groundwater such as public supply, industrial supply or river augmentation. It will make the sustainable city more attainable.

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A dual isotope method for identifying denitrification in a sand and gravel aquifer in Eastern Germany

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The identification of denitrification in the Torgau sand and gravel aquifer, Eastern Germany, was conducted by measuring the $?^{15}N$ and $?^{18}O$ in NO_3^-. Samples were prepared by an anion exchange resin method (Silva *et al.*, 2000) with a modification. The occurrence of denitrification was confirmed by comparing the water chemistry data with the dual isotope signatures. The denitrification accords with a Rayleigh equation for both the $?^{15}N$ and $?^{18}O$ data. The slope of the straight-line relationship between the $?^{15}N$ and $?^{18}O$ demonstrated that the enrichment of the heavy nitrogen isotope was higher by a factor of 1.3 compared with the heavy oxygen isotope. It is concluded that the identification of this factor is a useful means for confirming denitrification in future groundwater studies.

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Towards a generalised linear model of groundwater pollution by pesticides

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This study brings together extensive groundwater monitoring datasets from the UK and the US to examine the underlying controls on the causes of groundwater pollution by pesticides. The study firstly examined the role of chemical properties in controlling occurrence in groundwater, secondly, the role of the properties of the site of application, and finally, brought these factors together to test their relative importance and propose combined models based on both site and chemical properties. The study:

1) developed an model of the occurrence of pesticides in groundwater based on molecular topology;

2) developed a method of calculating groundwater vulnerability, independent of compound type, directly from borehole observations;

3) showed that groundwater vulnerability in agricultural catchments was governed by soil and hydrologic factors, but was independent of land-use;

4) showed that both chemical and site factors have an independent and significant effect on groundwater contamination, but that the interaction of these factors is the important control; and

5) developed a model for the prediction of occurrence in groundwater that combines vulnerability with molecular properties.

These methods are leading to a generalised linear model of groundwater pollution by pesticides that brings with it new opportunities in risk assessment and risk management.

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Nitrates: Protection of groundwater using spatial and geostatistical analyses

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A new approach for defining land zones to protect groundwater resources from the effects of agriculturally derived diffuse nitrate pollution has been developed. The approach combines a risk-based approach with one that is data derived and operates in two distinct stages. The first stage collates and statistically examines groundwater nitrate data from all available monitoring points. At the same time a number of groundwater vulnerability scenarios are modelled to determine the theoretical risks to groundwater based on land use, climate, soil and (solid and Drift) geological characteristics. The maps derived from this latter exercise are compared with the monitoring data to determine which of the scenarios best predicts the vulnerability of groundwater to nitrate pollution. In the second stage, the spatial distribution of nitrate concentrations is estimated by geostatistical analysis of the monitoring data and is used in conjunction with the selected vulnerability map to define protection zones.

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What's over the horizon? – An Environment Agency perspective on future research needs

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Hydrogeology is still a very young science and in its development has, perhaps understandably, rather isolated itself from other water and land based science focused on the rest of the (water) environment. Although many separate issues need to be considered within the unique sub-surface environment, the effective environmental management of river catchments and the ecosystems they support will inevitably demand a more holistic understanding of the basic science of the underlying processes. For example, the important role that groundwater plays in supporting rivers and terrestrial ecosystems has to be more readily understood. A major driver for this change is the European Water Framework Directive. This will require not only a better understanding of the interconnected flow processes but of the natural and man-made pollutant fluxes between all parts of the hydrological cycle - groundwater, rivers, lakes, estuaries etc – and the impact they have on the respective ecosystems.

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