'Water Futures'

6 - 7 March 2012

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Oral Presentation Abstracts

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Tuesday 6 March

Theme 1: Groundwater and Energy

Deep Basinal Pore Fluids – An Underused Resource?

Jon Gluyas[1] and Susie Daniels[2]

[1] Durham Energy Institute, Durham University, Durham, DH1 3LE, UK
[2] Geospatial Research Limited, Durham University, Durham, DH1 3LE

In 2010 3.8 billion tonnes of oil and 2.8 billion tonnes of gas were extracted from the earth. The volume of waste water produced alongside is 2-10 times the oil volume (i.e. 7 – 38 billion tonnes of co-produced water). With an average water temperature of 100ºC, this equates to 2,600 - 13,000 megawatts of untapped electrical power. In 2010 the world produced about 11,000 megawatts of geothermal power. Use of the oil industry's waste water could double global geothermal electricity production.

The total quantity of water injected into the earth to support oil production is not known but in most provinces the voidage replacement ratio is about unity after initial pressure depletion, and hence we can assume that the annual water injection is marginally less than the total of oil plus water produced (10-41 billion tonnes of water). CO_2 is also injected into the earth at a typical rate of ~55 million tonnes of CO_2 per annum, through both carbon storage pilot schemes (<5 Mt) and enhanced oil recovery operations (~50 Mt). In contrast 31 billion tonnes of CO_2 are emitted to the atmosphere annually. CO_2 is more efficient than water at sweeping oil reservoirs. Using above estimates of global water injection volumes, we have the potential to bury most global CO_2 emissions while enhancing oil production.

Today there is little overlap between the petroleum, geothermal and developing CCS industries. Yet it would seem that an integrated approach to use of deep basinal pore water and associated fluids could reduce waste and hence improve performance of each industrial component.

NOTES

Effects of CO2 storage on shallow groundwater resources: a hypothetical case study in the Sherwood Sandstone aquifer, UK

Bricker[1], S.H., Barkwith[1], A., MacDonald[2], A.M., Hughes[1], A.G. and Smith[2], M.

[1]British Geological Survey, Kingsley Dunham Centre, Keyworth, Nottingham, NG12 5GG, UK.
[2]British Geological Survey, Murchison House, West Mains Road, Edinburgh EH9 3LA

The far-field effects of CO2 storage on onshore potable groundwater systems is examined for a hypothetical injection site within the Sherwood Sandstone Group on the East Lincolnshire coastline, UK. Using the quasi-three dimensional object-orientated groundwater flow model ZOOMQ3D, supported by conceptualisation and aquifer parameterisation of the wider hydrogeological setting, injection of 15 Mt of CO2 (60 Ml/day groundwater equivalent) into the aquifer at depth is simulated. Model scenarios are carried out which test the dissipation of pressures up-dip within the storage formation. When applying typical vertical hydraulic conductivity of 10-6 m/day to the Mercia Mudstone Group caprock groundwater pressure heads in the shallow confined SSG aquifer, 60 km up dip, where it is used for potable water supply, increase by 0.01-10 m. Groundwater levels within the unconfined aquifer, 80-100 km up-dip from the injection zone, increase by <0.01m to 1m with a corresponding increase in river flows of approximately 1.7%. Two important points are observed, firstly that the degree of impact on shallow groundwater systems is highly sensitive to the vertical leakage assigned to the caprock. When the leakage co-efficient is increased by one order of magnitude groundwater heads in the potable aquifer are reduced by two orders of magnitude. Secondly, that the response of groundwater pressure heads to injection is rapid, as is the subsequent recovery. Using a groundwater model, in addition to detailed reservoir modelling, provides a useful tool to assess the potential scale of impact of CO2 storage on shallow groundwater systems and can be used to aid regulation.

NOTES

Shale gas and groundwater

Mike Stephenson, *British Geological Survey, Kingsley Dunham Centre, Keyworth, Nottingham NG12 5GG.*

Shale gas is held within micro-pores and fractures and is also adsorbed onto organic matter in shale. The flat, clay mineral grains that form layers in shale result in a sediment which has extremely low vertical permeability but some horizontal permeability. The low permeability means that gas is trapped in the shales and will not flow of its own accord so fracturing methods are used to free the gas for production. Typical permeabilities for unfractured shales are 0.01 to 0.00001mD. A considerable volume of water is used for formation fracturing. Around 60 per cent of this water will return to the surface via the borehole. It is likely to be saline and may be contaminated with other material. As a result, this water will require treatment prior to discharge, although its re-use in the fracturing process is possible.

But the most pressing concern at present is that fracturing will contaminate nearby aquifers with methane, or allow an increase in methane discharges direct to the atmosphere (so-called fugitive emissions). Contamination of groundwater by the chemicals used to enhance the effectiveness of hydraulic fracturing is also of concern.

Most geologists think that methane or frack fluid contamination of aquifers is unlikely because of the great difference between the depths at which fracking activities are usually carried out and the aquifers from which we get our water. However there are relatively few peer-reviewed studies of methane contamination during shale gas fracking, and rather problematically, there are few baseline studies of amounts of natural methane in groundwater.

There are a number of methods that we can use to distinguish biogenic and thermogenic methane and even distinguish between thermogenic methane generated at different times in the geological history of a sequence of rocks. But the use of these methods is confused by the natural mixing that goes on when gas moves in the subsurface, and by the fact that we use the subsurface for other activities, e.g. reservoirs to store gas for 'peak shaving'.

Some of the studies of purported groundwater contamination by methane are presented as well as an introduction to the role of the British Geological Survey in shale gas development in Britain.

NOTES

Open-loop GSHP tool for the initial assessment of suitability in England and Wales

Corinna Abesser[1], Jon Busby[2], Melinda Lewis[1], Rose Hargreaves[1] and Michael Lord[2]

[1]*British Geological Survey, Maclean Building, Crowmarsh Gifford, Wallingford, OX3 8EA*
[2]*British Geological Survey, Kingsley Dunham Centre, Keyworth, Nottingham NG12 5GG*
[3]*Environment Agency, Horizon House, Deanery Road, Bristol, BS1 5AH*

The Government expects that by 2020 12% of the UK's heat demand will come from renewable sources, and is providing incentives to help achieve this. Ground source heat pumps (GSHPs) extract/input heat from/to the ground and could make a substantial contribution as they provide an energy-efficient, low-carbon alternative to traditional heating /cooling systems. At larger scales (100kw +) open-loop GSHPs can be more economic than closed-loop systems. However, they rely on certain hydrogeological conditions. This tool gives potential developers an indication of whether these conditions exist at a given location.

Using national-scale data sets, a tool is developed within a GIS that maps the potential for open-loop GSHP installations (heating/cooling output >100kwh) in England and Wales at the 1:250,000 scale. The tool is developed by the BGS and the Environment Agency in close consultation with experts from the ground source heat pump industry. It considers hydrogeological and economic factors, including productivity of the aquifer and depths of abstraction, as well as potential restrictions (e.g., location within a source protection zone). It also has potential to include geochemical information.

Data are collated, grouped and summarised within a GIS environment and suitability for GSHPs is displayed in the form of a map and tables. Ranking and weighting of the data was deliberately avoided as these methods conceal the actual parameter values which are of great importance for the planning of GSHP schemes. As such the tool provides an effective instrument for assessing the GSHP suitability of a location at the given scale.

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How will planting bioenergy crops change potential recharge?

Dr Jon Finch, *Centre for Ecology & Hydrology*

In response to concerns about climate change and energy security, the UK government's policy is for a shift in energy production from the current situation, where the market is dominated by fossil feedstocks, to the use of other sources. Renewable energy sources are an important part of this change and bioenergy is anticipated to provide about 10% of the UK's energy requirements. There is an aspiration that a large amount of the feedstocks will be produced in the UK. Currently, most bioenergy uses feedstocks that are food crops, e.g. bioethanol from wheat. However, there will be a growing market for so called biomass crops – when the entire above ground biomass is used. These biomass crops are very different from conventional crops and so there is the possibility of major land use change occurring in the UK. A major issue is how the water loss, through evaporation, differs from that of the existing land use which they might replace. In order to be economic to grow, a high production of above ground biomass is required which it is likely to be linked to a high water loss. Research has shown how the water loss of the two dominant biomass crops in the UK (willow, managed as short rotation coppice, and Miscanthus, a semi-tropical C4 grass) compare to the existing land uses. However, in order to assess the potential impact on groundwater bodies, it is also necessary to consider where these crops are likely to be grown. Two factors act to constrain where these crops will be grown: the yield of the crop and the nature of the landscape, e.g. excluding urban areas. Further refinement of the cropped areas is more challenging as it depends on the location of the energy production centres and the decision of individual farmers as to how these crops fit into their business plans.

NOTES

Tuesday 6 March

Theme 2: Groundwater and Basin Scale Processes

Effects of Faults on Geofluids in the California Borderland Basins

Grant Garven, *Department of Geology, Tufts University, Medford, Massachusetts, USA*

Sedimentary basins are subjected to a myriad of dynamic forces that affect regional groundwater flow, diagenesis, and deformation. Faults are known to affect groundwater quality and petroleum migration in coastal aquifers/reservoirs within the young borderland basins of southern California. In this paper we focus on major structures in the Santa Barbara and Los Angeles basins. Subsurface geology, geophysical logs, fluid P-T-X data, seafloor seep discharge patterns, fault mineralization paragenesis, fluid inclusions, and structural models help characterize the hydrogeologic effects of faults in this seismically-active and young geologic terrain. These data also provide constraints for mathematical models that are being developed for forward simulation purposes. Unique submarine seep data from the Santa Barbara basin help constrain fault permeability for large-scale migration of geofluids. Additional numerical simulations also are being developed to characterize the deep hydrogeology of the Los Angeles basin for both single- and two-phase fluid migration. Single-phase flow models simulate the basin-scale groundwater flow associated with basin subsidence and recent uplift of the San Gabriel Mountains (Fig. 1). Two-phase flow models also have been constructed to characterize both water and petroleum seepage at the formation scale. These models quantify rates and patterns of fluid migration and illustrate how major faults produced stacked petroleum reservoirs and the richest known accumulation of hydrocarbons in the Earth's crust. The modeling results suggest a geologically young history of fluid flow from the depocenter towards the south flank of the Los Angeles basin and the Palos Verdes Peninsula. The models also predict a natural preference for hydrocarbon accumulation along major faults, which appear to act as barriers for lateral flow but conduits for vertical flow.

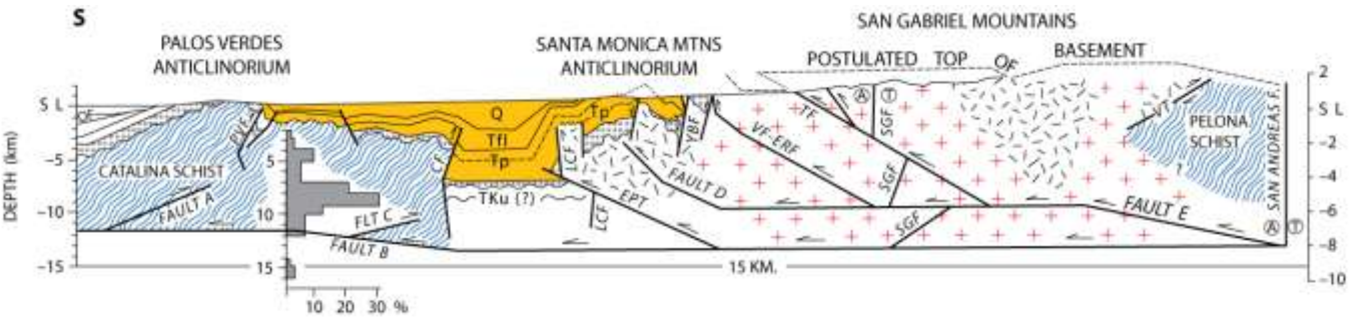

Figure 1. Structural cross section of the Los Angeles region (after Wright, 1991). Profile orientation is from southwest to northeast (left to right). The Los Angeles basin (yellow) contains several kilometers of partially-cemented arkosic sandstone and organic-rich mudstone.

NOTES

Enhancement of basin-scale permeability in limestones by sulfate dissolution

Simon Bottrell[1], John Gunn[2] and Stephen Worthington[3]

[1]*School of Earth and Environment, University of Leeds, LEEDS LS2 9JT, UK*
[2]*Limestone Research Group, GEES, University of Birmingham, BIRMINGHAM, B15 2TT, UK*
[3]*Worthingron Groundwater, Dundas, Ontario, Canada, L9H 3K9*

Groundwater flow paths and processes in limestones can only be fully understood by considering them on a basin scale. Local flow systems tend to be dominated by calcium and bicarbonate from shallow dissolution of limestone. The presence of thermal springs with high sulfate concentrations at basin margins attests to the deep dissolution of gypsum.

In Indiana monitoring of hydrographs, spring chemistry and sulfate stable isotopes from karst springs led to the identification of a deep "underflow" component of spring discharge that contained elevated sulfate that originated from dissolution of sulfate evaporite minerals. Dissolution of sulfate evaporites produces a diagnostic hydrochemical signal in the predictable isotopic composition of S and O in the resulting dissolved sulfate. We use this indigenous tracer to search for and identify this process in limestone aquifers in a variety of settings.

In Derbyshire, some 5% of groundwater flow from a 540 km^2 Carboniferous Limestone outcrop is in the form of sulfate-enriched thermal groundwater. The sulfate has characteristic Carboniferous evaporite isotopic composition and evaporites are known from deep boreholes. The rate of sulfate export in thermal groundwater corresponds to 2300 tonnes of gypsum per year. This is equivalent to 1100 m^3 of porosity generation per year (or 1 mm/yr increase in aperture over a 1000 km network of 1 m wide fractures), a significant rate of porosity development in the deep aquifer.

In the Cuilcagh karst of northwest Ireland, isotopic compositions of sulfate in water from a spring that is the source of the River Shannon also indicate evaporite dissolution as a source of sulfate during flood events. Furthermore, isotopic compositions of sulfate from the thermal springs in Carboniferous Limestones at Bath, traditionally interpreted as due to infiltration from overlying Triassic evaporites, would also be consistent with a Carboniferous evaporite source and might indicate evaporite dissolution associated with these deep groundwater flows.

Unlike carbonate dissolution, gypsum dissolution does not require water to be "aggressive" and is therefore far more easily accomplished at depth and with slow flow rates. Thus in the early stages of groundwater movement in carbonate rocks, preferential dissolution of evaporites will provide a more effective mechanism for tertiary porosity/permeability enhancement (and initiation of groundwater flow paths) than carbonate dissolution. The presence of a hydrochemical marker for evaporite dissolution in deep flows from limestone aquifers indicates that gypsum dissolution is a significant process in deep groundwaters. Worldwide many limestone springwaters have high sulfate concentrations, indicating that this process may be widespread.

NOTES

Reconstruction of fluid flow during burial diagenesis and Pb-Zn-F mineralisation within the Lower Carboniferous of the Derbyshire Platform, UK

Miles Frazer[1,2], Fiona Whitaker[2] and Cathy Hollis[1]

[1]*School of Earth, Atmospheric and Environmental Sciences, University of Manchester, M13 9PL*
[2]*School of Earth Sciences, University of Bristol, Bristol BS8 1RJ, UK*

Constraining reactive fluid sources and volumes is a major challenge in the reconstruction of carbonate diagenetic processes. Such quantitative constraints are required to evaluate conceptual models of diagenesis and allow more robust models to be developed. The Lower Carboniferous of the Derbyshire Platform, northern England, provides a data-rich environment where basin-scale numerical models can be used to provide these important constraints. The carbonate succession on the platform hosts economic volumes of Pb-Zn-F-Ba and its tectono-stratigraphic and diagenetic timelines are well established. This provides clear constraints for numerical simulations of fluid flow throughout the history of the system.The Lower Carboniferous succession on the Derbyshire Platform accumulated upon a footwall high during a period of extensional rifting. Rapidly subsiding basins surrounding the platform accumulated thick, syn-rift sequences of marine, carbonate-mudstones and thin limestones. This sequence was progressively buried by a southward-prograding, fluviodeltaic succession during thermal sag subsidence. Late Carboniferous, Variscan compression led to reactivation of basement faults which resulted in basin inversion. Current conceptual models of mineralisation suggest that overpressured fluids within upper syn-rift and post-rift basinal sediments were released at the onset of Variscan compression. Post-rift shales, rich in trace metals, are suggested as a potential source for mineralising fluids, but a mechanism to drive fluid downward, into the underlying platform carbonates is hard to constrain.

We use Basin2 to simulate coupled sedimentological and hydrological evolution of a single basin within this system. 2-D simulations of the Widmerpool Basin sedimentation history show 11.9 MPa of fluid overpressure develops throughout syn-rift and early post-rift sediments after maximum burial to 2.75 km. Upon fracture opening along platform margins, this overpressure drives approximately 1.45 km^3 of fluid out of these sediments per km of platform margin. Fluids are predominantly sourced from basinal mudstones and shales, although the timescale of release varies between syn-rift and early post-rift units. The simulations suggest a two-stage pressure release mechanism driving fluid flow through the fractured platform margins. Initially, fracture opening triggers lateral flow from basin-filling syn-rift sediments, predominantly sourced from mudstones and shales. Reduction of fluid pressures in these deeper sediments produces a vertical pressure gradient, generating slower downward flow from the shallower early post-rift sediments, via the syn-rift sediments, towards the platform margins. Thus stage-1 fluid release is characterised by a relatively short-lived, large volume release of deeper, hotter fluids sourced from more carbonate rich basinal sediments. Stage-2 is characterised by much lower flow rates over a much longer timescale. These later fluids are cooler, but are sourced from shales with high concentrations of trace metals. It is this stage-2 flow system that is suggested to form the Pb-Zn deposits hosted within platform carbonates. Sensitivity analyses show that overpressures and associated fluid fluxes are slightly reduced by calcite cementation in platform carbonates but are primarily controlled by seal-unit permeability and post-rift deposition rate.

NOTES

Tracing seawater evaporation and evaporite dissolution in the Zambian Copperbelt: Evidence from crush-leach analysis of fluid inclusions

J. P. Nowecki[1*], S. A. Gleeson[2], & S. Roberts[1]

[1]*National Oceanography Centre, Southampton, University of Southampton Waterfront Campus, European Way, Southampton, SO14 3ZH*
[2]*Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, AB, Canada*
**Corresponding Author: jpn205@soton.ac.uk*

A bulk fluid inclusion chemistry study was conducted via crush-leach on vein quartz and carbonate samples from a suite of copper deposits from the classic Copperbelt stratigraphy (Konkola, Konkola North, Nchanga), the basement in this region (Samba) and deposits and prospects from across the Domes region (Lumwana, Kansanshi, Kalumbila-Sentinel and Enterprise).

Cl/Br ratios indicate two main sources for the hydrothermal fluids related to these deposits. Konkola, Konkola North and Samba show Cl/Br ratios below that of seawater (Cl/Br = 658 [1]), characteristic of a fluid formed by evaporation of seawater beyond the halite saturation point. Enterprise and Kalumbila-Sentinel show Cl/Br ratios above that of seawater, indicative of an increase in Cl content caused by dissolution of halite in evaporite sequences. All veins within the ore zones at Nchanga show the seawater signature, whilst veins within the underlying granite show both the seawater signature and that of halite dissolution, suggesting multiple phases of fluid flow through the Nchanga basement. At Lumwana, paragenetically early boudins show the seawater signature, whilst late, discordant veins show the halite dissolution signature indicating a change in fluid source later in the deposit history. At Kansanshi, there is a degree of mineralogical control over the two signatures, with quartz showing mostly the halite dissolution signature, and carbonate mainly showing the seawater evaporation signature. Chlorine isotope data from vein leachates are clustered around 0 ‰, indicative of a crustal Cl source, and are all within the -1 to +1 ‰ range of seawater, evaporites and residual fluids formed after evaporite precipitation [2].

From these data, it is clear that the evaporation of seawater and the associated formation of evaporite deposits were critical in the fluid history of the basin. Though constraints on timing are limited, paragenetically early veins (boudins) show an evaporated seawater signature, whilst the halite dissolution signature correlates with veins which are paragenetically late in the history of the basin. This suggests a fluid event late in the basin history (post peak metamorphism) dominated by the dissolution of evaporites, whilst earlier fluid flow was controlled by the evaporation of seawater.

[1] Gleeson S.A. (2003). Bulk analysis of electrolytes in fluid inclusions. In Sampson et al., *Fluid inclusions: analysis and interpretation, Mineralogical Association of Canada Short Course vol. 32*. Chapter 9. 233-246.
[2] Eastoe C.J. et al. (2007). Stable chlorine isotopes in Phanerozoic evaporites. *App. Geochem*. **22**. 575-588.

NOTES

Impacts of small-scale geologic heterogeneity on large-scale groundwater flow: Implications for sustainable arsenic-safe water supply in the Bengal Basin

Holly Michael, *Department of Geological Sciences, College of Earth, Ocean, and Environment University of Delaware*

The sedimentary history of the Bengal Basin has determined the structure and pattern of an aquifer system more than 250,000 km^2 in area and up to 16 km deep. Rivers carrying huge sediment loads from the Himalayas have deposited and eroded floodplain sediments through avulsion cycles; this combined with transgressions and regressions of sea level have produced complex stratigraphic sequences that make up a highly heterogeneous hydrogeologic system.

The sedimentary architecture plays a major role in determining groundwater flowpaths and subsurface transport of solutes. The effects of both hydraulic and chemical heterogeneity in the Bengal Basin are considered in the context of sustainability of arsenic-safe groundwater resources. Widespread contamination of shallow groundwater with arsenic concentrations above world health standards occurs throughout much of the lower Bengal Basin. High concentrations are limited to the upper 100m in many areas; thus deep groundwater has been targeted as a mitigation option. However, pumping at depth may induce downward migration of arsenic from shallow, contaminated aquifer zones in areas where physical (groundwater flowpaths) and chemical (arsenic sorption or reaction) protection does not occur or is insufficient. Simulation on a regional scale assuming basin-wide effective properties suggests a sustainable resource if deep pumping is limited to domestic supply, with irrigation water obtained from other sources. However, simulations that incorporate explicit small-scale heterogeneity in physical and chemical properties indicate that arsenic migration may be highly variable, thus local field studies are essential for assessment of feasibility and variability across the basin and regular monitoring is recommended.

NOTES

Permeability anisotropy and patterns of arsenic distribution in the Bengal Aquifer System

Mohammad Hoque and William Burgess, *Department of Earth Sciences, University College London, London, WC1E 6BT*

Groundwater development in the Bengal Aquifer System (BAS) should have regard to the distribution of arsenic (As) in the aquifer, but comprehensive understanding of this distribution is elusive. We have interpreted >1500 lithological records from southern Bangladesh and developed models of groundwater flow and As transport which suggest an explanation of the naturally-determined spatial and depth distribution of As in BAS. The *SiHA hypothesis has three components - evolution of a heterogeneous, anisotropic BAS; topographically-driven groundwater flow; and redox-controlled transfer of As between solid and aqueous phases. We show that the very subdued basin topography, coupled with the presence of silt-clay layers, is sufficient to generate a hierarchical system of groundwater flow. Basin-margin, As-free regions are the sources for deep groundwater, as corroborated by a vertical profile of groundwater age established in SE Bangladesh in which age is invariant with depth at >100 m. The models illustrate the variety of observed patterns of As distribution in BAS, and explain (i) the low background level of As in groundwater at >150 m, other than exceptionally where (ii) absence of silt-clay layers has enabled deeper penetration of As-bearing groundwater; (iii) the sharp transition from As-bearing to low-As groundwater in depth profile; (iv) consistently excessive As at shallow depth in zones of relative groundwater stagnancy; (v) regions where shallow groundwater As is at low background level, beneath and adjacent to sites where topography imposes greater hydraulic gradients and effective groundwater flushing; (vi) steep lateral gradients in As concentration at the boundaries of groundwater discharge zones, including where the juxtaposition of older and younger groundwater, previously paradoxical, is an expected outcome under SiHA. We conclude that As has been restricted to shallow levels of BAS since the early stages of basin/aquifer development, and will remain so for as long as high-stand sedimentation continues in the basin. Deeper levels of the aquifer will remain at a low background As level, unless As is re-distributed by excessive pumping.

*SiHA: Silt-clay layers impose Hierarchical groundwater flow, constraining Arsenic progression

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Effects of geological heterogeneity on groundwater flow in the London Basin

Steve Buss, *ESI Ltd., 160 Abbey Foregate, Shrewsbury SY2 5HH*

The geological structure of the London Basin appears on the regional geology map to be that of a simple, plunging, syncline. But recent investigations for major civil engineering projects have highlighted that it is much more complex than it appears. Tectonic activity throughout its formation has led to considerable heterogeneity in sedimentary facies; and displacements and rotations at different scales across the basin. Meanwhile aquifer properties are also observed to vary across the basin; channels of very high transmissivity in the Chalk follow the paths of rivers 80 m or more above the top of the formation, separated by 50 m thickness of London Clay. Faults that traverse the basin resist groundwater flow along some lengths and not others.

During the twentieth century the aquifer has been subjected to considerable abstraction stress, leading to dewatering of layers within the aquifer; followed by a rapid recovery in groundwater levels that is now being controlled to protect essential underground infrastructure. In other areas the dewatering has created opportunities for exploitation for artificial recharge and recovery (ARR). Heterogeneity in aquifer properties has resulted in a heterogeneous response to these historical abstraction pressures.

This presentation shows results from the most recent groundwater model of the London Basin and, using results from model scenarios, highlights the hydrogeological importance of: spatial differences in Chalk transmissivity, vertical and spatial facies change in overlying formations, and faulting.

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Wednesday 7 March

Theme 3: Groundwater and Basin Scale Processes

Towards an understanding of anthropogenic stresses and hydrologic feedbacks on future groundwater resources.

Reed M. Maxwell, *Integrated GroundWater Modeling Center, Department of Geology and Geological Engineering, Colorado School of Mines, Golden CO USA*

The role of groundwater in the hydrologic cycle is often under-appreciated despite being an intricately linked component and a critical water resource. Groundwater plays an import role within hydrology, where land-energy fluxes that control recharge and land-atmosphere interactions are governed by water table depth. This interdependence in the critical zone has tremendous implications for climate change, especially when other anthropogenic activities which are often overlooked, such as pumping and irrigation, are considered. These activities impact the water table depth and therefore have implations for the land-energy budget. Findings from a carefully-controlled numerical experiment will be used to compare these seemingly disparate forcings on groundwater, drawing similarities between the effects of groundwater pumping, irrigation and climate change on land-energy fluxes and water balances. A case study where most of the Continental United States (a 6.3M km^2 domain encompassing the Mississippi and Colorado watersheds) is simulated using the ParFlow hydrologic model at high resolution (1km laterally) to understand processes, interactions, feedbacks and scaling will be presented. This case study demonstrates the role of integrated hydrologic modeling and high-performance computing as a tool for future understanding of groundwater resources.

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Effects of climate change on UK groundwater resources assessed using the UKCP09 probabilistic climate projections

C.R. Jackson, A. Barkwith, J. Mackay, L. Wang, C Prudhomme and G Watts, *British Geological Survey*

The effects of climate change on UK groundwater resources have been assessed using the UKCP09 climate projections for the coming century. Both the UKCP09 ensemble of 10,000 rainfall and temperature change factors, and the 11 regional climate model transient projections were used. These were applied to a distributed regional groundwater model of a Chalk aquifer of central-southern England and to simple lumped catchment models of other major UK aquifers. Simulated changes in groundwater levels and river flows will be presented. For the regional Chalk model these will be put in the context of previous results derived using projections from 13 global climate models reported in the IPCC Fourth Assessment Report. The work has been undertaken as part of the *Future Flows and Groundwater Levels* project co-funded by the Environment Agency, DEFRA, UKWIR, Centre for Ecology and Hydrology, British Geological Survey and Wallingford HydroSolutions.

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Dependence of groundwater resources on extreme rainfall: evidence from East Africa

Richard Taylor

Recharge sustains groundwater abstraction upon which there is global dependence for drinking water and irrigated agriculture. A newly compiled 55-year record of groundwater-level observations in central Tanzania reveals the highly episodic occurrence of recharge that results from years of statistically extreme (>80th percentile) rainfall. Recharge events interrupt multiannual recessions in groundwater levels and thereby maintain the water security of groundwater-dependent communities in this region. This rare, long-term record of in situ groundwater storage changes in the semi-arid tropics demonstrates a non-linear relationship between rainfall and recharge wherein statistically extreme rainfalls associated with SST anomalies (ENSO, IOD) contribute disproportionally to the recharge flux. As anthropogenic warming is projected to intensify rainfall not only regionally but globally, the record demonstrates the critical but currently overlooked importance of explicitly considering changes in rainfall intensity in the estimation of terrestrial water balances that include recharge

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Linking Groundwater and Climate: Learning from the Past and Looking to the Future

Kevin Hiscock, *School of Environmental Sciences, University of East Anglia, Norwich Research Park, Norwich NR4 7TJ*

Changes in climatic patterns since antiquity have determined water supplies and the survival of settled communities. Looking to the future, we are faced with the same challenge of adapting to climate change, now forced by the rapid increase in anthropogenic emissions of greenhouse gases and made more acute by global population pressures. In this presentation, the combined evidence for climatically-driven and human-induced pressures on groundwater resources will be reviewed. A global perspective will be adopted and measures for adaptation will be considered based on best practice groundwater management and the need for better groundwater governance.

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Climatic effects on recharge mechanism in the Chalk aquifer.

M. Smith[1], D.Pope[1], R.Phillips[1], V. Vergnaud[2], T. Labasque[2], L. Aquilina[2].

[1]*School of Environment and Technology, University of Brighton, Brighton, BN2 4GJ, U.K.*
[2]*Géosciences Rennes, Université de Rennes 1, 263 av du général Leclerc, RENNES, France.*

The mechanism of recharge to the water table in UK Chalk aquifers is of key importance to models of groundwater management, water quality and contaminant transport. Physical and chemical monitoring strategies implemented in the Patcham catchment, Brighton, as part of the EU-RDF funded FLOOD1 and CLIMAWAT programs indicate the susceptibility of recharge mechanism to climatic influences and artificial recharge practices. Monitoring of unsaturated zone matric potential indicates that significant negative pressures develop in the upper parts of the ground profile, but below ~15m matric potentials rarely drop below ~-100hPa. High frequency monitoring of groundwater conductivity indicates continuous trends with both recession and recovery, suggesting recharge dominated by slow matrix flow, although fracture flow does initiate once matric potentials have reached -50hPa, and when rainfall exceeds 10mm/day. Trends from a WWTW effluent dispersal site show periods of rapid change in conductivity, indicative of fracture flow when waste water dispersal maintains high matric potentials. CFC and SF_6 concentration data show complex trends across the catchment, with excess CFC concentrations, but data are consistent with mixing of recent and older waters (>20years). Overall the data indicate the operation of 2 recharge mechanisms (fracture flow and matrix piston flow), and a dependence of recharge mechanism on pre-existing matrix potential and the amount and rate of precipitation. Changes in precipitation pattern may lead to increasing incidence of rapid fracture flow with implications for water quality and contaminant transport.

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The Analysis of Observed Groundwater Levels to Predict Drought Impacts

Sarah Beeson[1], Robbie MacDonald[2] and Jan Van Wonderen[3]

[1] *Mott MacDonald Ltd*
[2] *Anglian Water Services*
[3] *Van Wonderen – Land and Water*

Relatively simple tools can be used to predict drought groundwater levels based on the analysis of data at observation boreholes. This is because no recharge occurs during droughts and most summers so that observed levels at these times reflect natural recessions against a background of regional abstractions.

The Groundwater Level Forecasting tool was developed in 2006 to predict future groundwater levels at 26 drought vulnerable groundwater sources located across East Anglia. This was triggered by concerns that a third dry winter following those of 2004/2005 and 2005/2006 would impact potential yields at these sources. The tool is controlled by the user who is required to select appropriate observed levels from the historic record at representative observation boreholes. The selected levels are then appended to the existing record to give the predictions. The predictions for 2006/2007 were, in most cases, almost identical to the levels that were observed subsequently.

Frequency analysis of historic observed groundwater level data can be used to assess the likely impacts on levels of the most severe drought in 200 years. Annual minimum levels fall on or close to statistically fitted probability distributions. The distributions indicate that levels during recent groundwater droughts, particularly that culminating in 1991, are likely to be no more than about 0.5 m above the 1 in 200 year minima. Of course, these minima have never been recorded. The dewatering of flow horizons below the minimum observed levels could be significant although these could be investigated by test pumping and downhole surveying.

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Smarter groundwater resource management as a component of climate change adaptation

Rob Solely, *AMEC*

The Environment Agency's 'Case for Change' explains why the current abstraction regulatory regime may not be fit to meet the future challenges of a changing climate and rising demands whilst avoiding ecological deterioration. The Water White Paper has initiated a debate on how regulation might become smarter to meet the changing needs of different sectors equitably and protect the environment. More innovative pricing strategies might also create a market for water which encourages a more integrated and optimised use of existing infrastructure (e.g. reservoirs) or incentivises investment to increase storage. Groundwater abstraction and smarter management of aquifer storage will play a key role within the broader and integrated strategy needed to adapt to these challenges. Borehole and well sources already provide reliable, local and often relatively cheap supply through dry periods with low flow impacts typically less than instantaneous abstraction rates. The return of a proportion of the abstracted water, or the operation of dedicated augmentation sources are also used to support low flows - as an alternative to the imposition of Hands Off Flow constraint rules which are rarely effective. The sustainability of such river support schemes can be questionable if they are ineffective (i.e. if water is pumped in circles) but, where low flows can be maintained, they may provide a valuable tool to meet local water needs of abstractors and the environment. A more comprehensive economic valuation of groundwater as an abstracted good compared with its value if left in the environment may also locally need to incorporate the abstraction benefits associated with alleviation of groundwater rebound or natural flooding events.

This talk will introduce the national GIS analysis behind the Environment Agency's illustrations of potential future water shortfalls published in their 'Case for Change' and will use specific examples of existing groundwater abstractions to generate discussion around ideas for smarter future management.

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Wednesday 7 March

Theme 4: Future Directions and Societal Challenges

Quo vadis Groundwater?

Johannes Grath

Due to the so called European Water Framework Directive 2000/60/EC and the Daughter Directive Groundwater 2006/118/EC many efforts concerning groundwater management and protection were made across Europe in the recent years. The above mentioned legislation initiated discussions, cooperation and a harmonised approach in all European Member States.

Important to mention - the discussions began already earlier: based on the declaration of the Ministerial Seminar on groundwater, held at The Hague in 1991, the EU groundwater action programme was developed and finally adopted by the European Commission in 1996.

It can be seen, the awareness for the importance of groundwater was already given twenty years ago at the policy level. In the meantime many changes and new challenges can be identified due to the rapid societal and scientific development.
Just some keywords to illustrate upcoming issues which might be of relevance for groundwater: shale gas, geothermal energy (deep and shallow), CO2-storage, production of bio fuel, climate change effects, gw-ecosystem functions, emerging pollutants, ….

Hence, it is important for the groundwater professional community to discuss and explore whether the policy in place seems adequate

- to tackle with new boundary conditions and pressures on groundwater and
- whether new scientific knowledge and understanding of the groundwater system may indicate the need for new complementary policies in order to save groundwater resources for the next generation.

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Groundwater Crisis?

Jacob Tompkins

There is a global water crisis. It is a slow and unrecognised crisis. In many parts of the developing world the crisis comes to public attention during times of drought and famine. But largely we are moving towards disaster. Globally we currently use 200,000,000 litres per second to grow food. A lot of this is green water falling as rain but a large proportion is from groundwater. At the same time domestic demand is growing in many of the worlds expanding cities, domestic demand in China, India and the United States is particularly worrying, with the first two growing rapidly and some US cities with a per capita daily consumption of over 1000 litres. This growth in domestic and agricultural demand is putting pressure on surface water and storage capacity, this is generally visible with falling river levels and empty reservoirs alerting the public to problems, but groundwater is a different matter, there is widescale mining of groundwater. At the same time increasing urbanisation is speeding up water flows within catchments and reducing the opportunities for infiltration. This groundwater mining combined with increased pollution potential and the loss of recharge is largely un-noticed and unchecked. There is a need to move from supplyside to demandside solutions and there is a need to develop an integrated approach to water management. Hydrologists and hydrogeologists must take a more political stance on these issues and must shape and influence water policy.

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Societal challenges and groundwater science

Rob Ward

Increasing population and demand for water means that by the middle of this century we will need around 75% more water than we currently use. Mostly this will be for agriculture and human consumption, and a lot of this additional resource will need to come from groundwater. At the same time there is an increasing realisation of the importance of the natural environment and the need to provide adequate protection to the sensitive ecosystems on which we depend. Balancing the needs of the environment against increasing human demand is a major challenge but when additional factors are taken into account it becomes even harder. The threat to groundwater from a wide range of pollutant sources continues to increase and whilst we have made efforts to address many polluting activities, new threats continue to emerge. Nearly 40% of groundwater bodies in England and Wales are at poor chemical status and a similar number are at poor quantitative status. The challenge is to restore these bodies to good status but with 30% of groundwater bodies also showing upward trends in pollutant concentrations is this going to be possible? A further challenge, particularly for water availability is the impact of climate change. What will this mean for the UK and other parts of the World dependent on groundwater?

Awareness of the environmental challenges we face is not enough on its own. We need better knowledge if we are going to successfully tackle them. There are no easy answers but science can, and must, play a vital role in helping us better understand the nature of the problems we face, quantify the potential impacts on society and the environment and develop effective solutions and mitigation measures. Groundwater science has an essential role to play as part of the multi-disciplinary approach we need to take if we are to make the right choices in the future to protect this precious resource. Groundwater contributes 25% of flow in rivers across the World (90% during the low flow season), 75% of drinking water across Europe (50% globally) and more than 95% of water for irrigation.

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The Future for Groundwater

Trevor Bishop, Head of Water Resources

Groundwater resources across England and Wales are under pressure. Many aquifers are subject to unsustainable levels of abstraction, reducing water levels and impacting on river flows, wetlands and wildlife. Pollution from agriculture, contaminated land and point sources is an ongoing threat.

Recent analysis of the impact of climate change has shown potentially significant changes in rainfall – and hence river flows and groundwater levels – by the 2050's. Reductions in resource availability will put further pressure on the water environment and security of water supplies.

The Government's Water White Paper "Water for Life", published in December 2011, makes clear that a reformed, more flexible approach to water resources management is needed by the 2020's. A key element of this includes a more integrated approach to surface and groundwater management, and the need to protect resources from increased pollution risk as a result of development and land management.

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Poster Presentation Abstracts
(in alphabetical order)

The adsorption performance of a novel, economic $TiO_2/\alpha\text{-}Fe_2O_3$ material for the removal of arsenic from drinking water.

F. Bullough, D. Weiss, A. Berry, *Department of Earth Science and Engineering, Imperial College, London, SW7 2AZ*

Consumption of elevated levels of arsenic is toxic and carcinogenic in humans. To satisfy the recommended maximum concentration (of 10 µg/L as established by the WHO), decontamination treatments must be capable of removing the predominant arsenite (AsIII) and arsenate (AsV) dissolved species. AsIII is ~60 times more toxic than AsV, more mobile, and has less affinity for standard adsorbents. This leads to unsatisfactory removal performance in groundwater, an important source of drinking water in Bangladesh which is susceptible to high AsIII concentrations

To address this issue a novel bicomposite, bi-functional $TiO_2/\alpha\text{-}Fe_2O_3$ adsorbent has been developed and tested. This material integrates (i) the photooxidation of weak adsorbing AsIII to AsV under UV irradiation and (ii) the adsorption performance of AsV on the iron phase, in addition to being simple and cost-effective to synthesise. The bi-composite material is therefore able to both reduce the arsenic toxicity by oxidation of AsIII to AsV and improve its adsorption performance by conversion to AsV.

The bi-composite material has been synthesised through various different methods and Ti:Fe ratios to optimise and assess the impact of precursor materials, method and metal ratio on the AsV removal performance. These materials were characterised through standard techniques to confirm the metal phase, size and morphology of the synthesised powders. AsV adsorption experiments were completed for all materials and a commercially used iron oxide adsorbent, Bayoxide, for comparison. The three highest performing materials had Langmuir Q_{max} maximum values of 28.17 mgAs/g$TiO_2/\alpha\text{-}Fe_2O_3$, 26.53 mgAs/g$TiO_2/\alpha\text{-}Fe_2O_3$ and 30.58 mgAs/g$TiO_2/\alpha\text{-}Fe_2O_3$ for the three metal ratios at pH 5. These experimental data show that the new materials have comparable performance to that of Bayoxide at 32.15 mg/g under the same conditions.

Examining the extent of ground water circulation in a high temperature geothermal system

Fran Entwistle[1], B. W. D. Yardley[1], C. A. Rochelle[2], T Milowdowski[2]

[1]*University of Leeds, Woodhouse Lane, LS2 9JT*
[2]*BGS, Kingsley Dunham Centre, Keyworth, Nottingham NG12 5GG*

High temperature geothermal fields mine heat from young igneous rocks through groundwater convection. There is now interest in extracting extra heat from the hotter rocks beneath currently-exploited regions of geothermal fields.

In geothermal fields, temperature initially increases with depth close to the boiling curve, but after a few hundred meters below the water table there are rather uniform temperatures, reflecting fluid convection.
Beneath the geothermal field temperature increases rapidly towards the underlying magma chamber. It is unclear how thick the thermal boundary layer is, whether groundwater enters it and whether it could be mined for heat.

Lavas around the Cuillin gabbro on the Isle of Skye provide a fossil analogue to geothermal systems in Iceland. Samples taken from around the intrusion provide evidence of a high temperature thermal boundary layer between <2 and >100m thickness surrounded by an extensive geothermal field. Existing stable isotope studies from this intrusion reveal a light δO^{18} signature, which has been interpreted as the result of ground water circulating through the thermal boundary layer and possibly interacting with magma. Initial results from high temperature (not hydrothermally altered) rocks still show this effect, but what is unclear as yet is the stage in the thermal history at which this interaction occurred, or indeed whether the light δO^{18} signature is a result of assimilation of older hydrothermally altered rocks by magma.

A study on road salt application on the M4 Motorway at Membury

Craig Hampton, *Environment Agency, Red Kite House, Wallingford, Oxon, OX10 8BD.*

The colder winters of 2009-2010 and 2010-2011 increased awareness in the UK of the need for road salt application. A recent study close to the M5-M42 motorway intersection by Rivett et al. (2011) indicated that chloride levels within the aquifer were rising, was this only a local trend? We in West Thames area of the Environment Agency were aware we had chloride data stretching back to 2001 for a motorway soakaway on the M4 near Membury. This data was collected following a chlorinated solvent pollution incident. Additional up and downgradient samples were also taken at private abstraction wells in the Chalk aquifer to delineate the contaminant plume.

Chloride concentrations in the soakaway reached nearly 2000 mg/l but dilution within the Chalk aquifer reduced concentrations to around 300 mg/l at the water table. Actual chloride concentrations were compared to ConSim models and a reasonable fit was achieved once the impact from additional motorway soakaways was factored in. The chlorinated solvents acted like a tracer having only affected a single soakaway. The model results indicated predominantly fissure flow occurs although dispersion within the matrix further reduced chloride concentrations to 10 mg/l above background levels 1 kilometre from the soakaway. The expected correlation of increased chloride concentrations with cold winters at the soakaway was observed. Within the aquifer however changes in water level (up to 10 metres) appeared to be the main impact on chloride concentrations. There was no evidence of any long term increasing trends in chloride levels at this location.

Rivett M.O et al. (2011) Winter 2009-10 at the M5-M42 junction, Birmingham: where did that all that salt go? Geological Society Conference: The Transport and Fate of Groundwater Contaminants 9 Feb 2011.

Mapping the Groundwater Flooding Hazard in the Republic of Ireland

Rachel Hardisty, *Mott MacDonald Ltd*

The European Floods Directive required nation states to identify areas of potentially significant risk from groundwater flooding as part of a preliminary flood risk assessment. A methodology for mapping the hazard of groundwater flooding was developed for the Office of Public Works in the Republic of Ireland and used to produce a preliminary nationwide groundwater flood hazard map. The methodology was required in order to adequately account for the low-lying karstic nature of a significant area of the hydrogeological environment in Ireland.

The methodology is based on a consideration of physical variables and the areal variability of the karstic hydrogeological environment as these control the amount, location and extent of groundwater floods. Information used in the mapping includes: evidence provided by groundwater experts; reports held on a database of flood events; digital images from aerial photography; satellite images of historic floods; and topographical elevations derived from a digital terrain model. The methodology comprises three interlinked stages, which differ from each other in terms of the amounts and quality of available information.

The methodology could be applied to the mapping of groundwater floods associated with low-lying karstic environments elsewhere in Europe.

Modelling large scale fluid mixing in crystalline bedrock using water 87Sr/86Sr isotope data

Jason Go[1], Imma Bortone[1], Craig Smalley[2], and Ann Muggeridge[1]

[1]*Department of Earth Science and Engineering, Imperial College, London, SW7 2AZ*
[2]*BP, Sunbury-on-Thames, Middlesex TW16 7BP*

Understanding and monitoring of groundwater composition is important in order to identify basin scale flows and predict the potential impact of contaminants on the groundwater quality.

In this paper we a) present an analytical model that predicts the distributions of groundwater tracers in layered systems over time and b) use the model to evaluate mixing of 87Sr/86Sr isotopes with depth, using data from a bore hole in Outokumpu Ore province (eastern Finland). The model includes adsorption by the formation rock, molecular diffusion and different hydraulic properties between layers.

Stratification of formation waters in crystalline bedrock may be due to large-scale mixing process and/or local water-rock interactions. Previous studies in the Outokumpu Ore province have shown three distinct compositionally stratified groundwater zones: fresh water zone A (87Sr/86Sr > 0.730) underlain by two saline water zones B (87Sr/86Sr > 0.724) and C (87Sr/86Sr > 0.723). It was postulated that the stratification was a result of water-rock interaction with various bedrock lithologies, overprinted by large-scale mixing processes.

Good agreement was observed between the predicted Sr-isotope depth profiles and the observations from the borehole. Diffusion through the lower saline water zones was significantly slowed down by increased tortuosity and sorption in that zone. The predicted mixing time-scales are consistent with the apparent radiocarbon age of sample groundwaters from nearby boreholes, which is of the order of several thousands of years (consistent with the timing of the last deglaciation in Finland).

Role of non-Darcy flow on salt precipitation during CO2 sequestration in saline aquifers

Ana Mijic[1], Tara LaForce[2] and Ann Muggeridge[1]

[1] *Earth Science Department, Imperial College London*
[2] *CSIRO, Australia*

Saline aquifers are an important resource for the underground storage of CO_2; however injection of CO_2 may result in salt precipitation around the injection well. This precipitation is a function of, amongst other factors, the flow regime around the well. Excessive precipitation will tend to reduce the hydraulic conductivity of the rock and hence impair injection.

This work presents an analytical solution to predict where the salt precipitation will occur, using a Forchheimer type equation (rather than Darcy's equation) for the two-phase flow. The results enable the determination of a drying front, where the CO_2 evaporates the residual brine, and hence the zone around the well where the salt precipitation will occur. By implementing the approximate solution for the solid salt saturation distribution it is shown that non-Darcy flow has a significant influence on saturation profiles and hence on reduction of injection rate. In addition, the non-Darcy displacement dependency on injection rate further contributes to the modification of the salt precipitation pattern.

"Design and Development of an Arsenate Selective Chemosorbent"

Christopher Moffat, Ramon Vilar and Dominik Weiss

Arsenic contamination of groundwater used for drinking is problematic across the globe. The health problems caused by arsenic are numerous, including cancer, cardiovascular disease, gastrointestinal and renal diseases, and neurological disorders.[1] The WHO guideline of 10 μg/L maximum concentration for arsenic in drinking water is regularly exceeded in countries such as Bangladesh, Vietnam and parts of India. High arsenic levels have also been found in many other countries across the world including the USA and Japan.[2]

Aqueous arsenic is commonly found in one of two oxidation states, As^{V} (arsenate) or As^{III} (arsenite).[3] Arsenate exists in water as a tetrahedral oxyanion, and thus represents a more suitable removal target than neutral arsenite.

The aim of the work presented here is to develop an adsorbent material consisting of a chemical arsenate receptor attached to a solid support, which will selectively remove arsenate anions from water. The use of receptors known already to provide selectivity towards tetrahedral oxyanions will result in an adsorbent material which binds arsenate strongly and selectively.

Two di-zinc complexes have been prepared and characterised. Binding of oxyanions under aqueous conditions was investigated through indicator displacement assays (IDAs) and isothermal titration calorimetry (ITC). Theoretical studies (DFT calculations) indicated binding strength would decrease in the order $HAsO_4^{2-} \geq HPO_4^{2-} > SO_4^{2-} >> CH_3CO_2^{-}$, which agrees well with experimental results. Single crystal X-ray crystallographic analysis of crystals of arsenate bound to one of the di-zinc receptors has been carried out providing details of the arsenate binding mode.

Binding constants between the receptors and different oxyanions were determined, showing that the di-zinc receptors are selective for arsenate and phosphate over sulphate, with $K_{As} > 10^4 M^{-1}$.

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(2) Mohan, D.; Pittman, C. U. *Journal of hazardous materials* **2007**, *142*, 1-53.
(3) Smedley, P. L.; Kinniburgh, D. G. *Applied Geochemistry* **2002**, *17*, 517-568.

Potential Inflow of Subglacial Groundwater to Proglacial Lakes Along the Margin of the West Greenland Ice Sheet

Johanna Scheidegger and Victor Bense, *School of Environmental Sciences, University of East Anglia, Norwich*

In the Kangerlussuaq area, West Greenland, the proglacial area stretching from the margin of the Greenland Ice sheet (GrIS) to the coast was covered by the GrIS during the last glacial maximum (LGM). Permafrost is several hundred meters deep and through taliks are believed to occur underneath large lakes providing sufficient thermal insulation. Nevertheless, observations have shown that a small lake, after partial lake drainage, refilled itself within a few of months. Considering heat conduction only, a thermal through talik is unlikely; however, we hypothesise that advective heat flow by groundwater discharge could have resulted in conditions that have locally hampered permafrost development after retreat of the GrIS. Regions in front of an ice sheet are subject to high hydraulic head gradients if the ice-base is wet, and groundwater flow paths can extent into the proglacial area where upwelling to the surface can potentially occur via localized high permeable zones.

In this study, we aim to improve our understanding of the occurrence of groundwater flow in permafrost covered areas. Firstly, with numerical modeling of coupled transient heat and fluid flow, we develop a 2D regional- scale hydrogeological model of an ice sheet covered area from which the ice retreats starting from the end of the LGM to its present position. In the forefield of the ice-sheet we mimic lake formation. In this way, we study the possibility of the development of through taliks due to advective heat flow through groundwater discharge. Secondly, we installed a Distributed Temperature Sensing (DTS) in a small lake in front of the ice sheet margin and monitor temperatures at the lake base in winter 2011/2012. DTS measurements monitor temperature across the lake bed, any episodic thermal anomaly which might arise from groundwater inflow across the lake bed.

Results show that due to high hydraulic head gradients, the proglacial area is subject to groundwater discharge. During the freezing process, groundwater discharges preferentially through taliks underneath lakes. Some of them remain open over the period since the LGM, whereas a conduction only model with the same settings would not show a through talik.

The comparison of a model of a single lake with a high hydraulic head, as it can be found in front of an ice sheet with a model without fluid flow, reveals that the through talik freezes down within a few hundred years, whereas in the same setting but with consideration of advective heat flow due to subsurface flow, the through talik can persist.

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Ground Floor Plan of the Geological Society, Burlington House, Piccadilly