Chlorinated solvents in groundwater:
Overcoming scale limitations of site characterisation and remediation after effects

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Chlorinated solvents have become notorious groundwater contaminants with billions now spent worldwide on their subsurface investigation and remediation. Although technologies have advanced and successes are more frequent, significant challenges remain at the field-scale. This PhD studentship focuses upon field-scale challenges and is supported and facilitated by *Geosyntec Consultants, Inc.* (Geosyntec; www.geosyntec.com), an employee-owned international consulting firm with over 800 professionals in offices throughout the United States, Canada, Malaysia and Australia, with planned offices opening in the UK in 2012. Geosyntec, with the University of Birmingham, has identified three possible options for PhD research that represent significant on-going challenges to practitioner and science communities alike: i) Scale issues and heterogeneity limitations in characterizing fractured bedrock sites; ii) Real time, remote monitoring and visualization of remedial technologies; iii) Impacts to aquifer and aquitard ecosystems from in-situ remediation Investigation. Applicants should indicate their preferred option(s) for study with supporting rationale. Field research will focus on site characterisation and/or remediation activities and will need to find synergy with Geosyntec's active projects, thus providing significant in-kind and two-way benefit. For example, this could involve use of more innovative, higher spatial/temporal resolution, or automated techniques. Geophysics collaboration has been agreed with the BGS that will allow remote collection of high spatial-temporal resolution 4D imaging data. Quantitative field data interpretation is anticipated likely involving statistical and modelling techniques. Upon appointment to this studentship and development of a project plan, appropriate linkages will be established with Geosyntec in the North America and UK as well as with BGS, as appropriate. This programme represents a significant learning and professional opportunity for the student complemented by the wide ranging expertise of Birmingham's Water Sciences research group and access to the MSc Hydrogeology taught programme. Suitable student backgrounds may be from geosciences, hydrogeology, environmental engineering, environmental and natural sciences.

Background research issues and aims that could potentially be addressed under the three research options are indicated below – these are by no means exhaustive and interested applicants are welcome to develop these ideas further. A hybrid of these options could likewise be developed. The aim is to progress the research through engaging with Geosyntec's on-going site investigations and remediation projects. We have successfully used similar PhD case approaches with consultants before.[1] Geosyntec will hence provide significant in-kind benefit to the PhD studentship and will additionally contribute £10k to research costs. The student will be permitted some leave from the PhD to contribute time to consulting with Geosyntec during the PhD, thus benefiting from paid employment and a more in-depth professional experience.

Option i) Scale issues and heterogeneity limitations in characterizing fractured bedrock sites
Fractured bedrock or dual porosity aquifer systems contaminated by DNAPL (dense non-aqueous phase liquid) chlorinated solvents are amongst the most difficult to characterise. Much of the spilt contaminant mass, at least initially, exists within a complex fracture network. With time, however, mass may diffuse from factures to a porous rock matrix. DNAPL sources at most sites are decades old and some mass may have re-distributed to the matrix. It is important to understand from both longevity of source-term predictions and effectiveness of remediation technologies where chemical mass is located. Standard site investigations typically fail to adequately resolve spatial distributions and controlling factors. The research aims to develop improved characterisation methods for fractured bedrock - DNAPL sites; to determine scales of measurement appropriate to adequate and cost effective source area characterisation; to develop relationships between characterised fracture

densities, matrix porosity, DNAPL mass and dissolution fluxes. Findings will underpin development of tools to quantify source-term and remediation potential of DNAPLs in fractured rock environments.

Option ii) Real time, remote monitoring and visualization of remedial technologies
In-situ remediation of DNAPL – chlorinated solvent source areas has undergone significant evolution in the last decade or so with a plethora of technologies now available. Geosyntec have been at the forefront of technology development and application (see www.geosyntec.com). This includes their successful commercialization of the well-known microbial inoculant KB-1™ for chlorinated solvent bioremediation. Typically a train of adaptive treatments may be preferred to accelerate and optimise site clean-up responding to changing site conditions as sources deplete and physical – biogeochemical conditions evolve. The research aim is to develop and, or apply improved methods that visualise remediation progress in real time, ideally remotely, or with minimal intrusion. Such methodologies and their application will provide insight to processes constraining remediation progress and facilitate adaptive remediation decision making. Collaboration with the BGS will allow use of high spatial-temporal resolution 4D geophysical imaging methods using remote in-situ logging systems that can be operated remotely using wireless telemetry. These technologies are minimally invasive, and offer an effective means of assessing subsurface heterogeneity, and volumetrically imaging biostimulation fluid distribution and groundwater quality changes over time. These methods will be combined with more chemical-based methods to assess remediation progress.

Option iii) Impacts to aquifer and aquitard ecosystems from in situ remediation Investigation
The focus of most remediation attempts us understandably on the contaminants of concern and their removal. Whilst remediations may be wholly successful in this primary goal, there are, however, often unwanted side effects on water quality that may still render the water unfit for human consumption or potentially problematic to other environmental receptors. Anaerobic boremediation of chlorinated solvents may typically involve the introduction of electron donor that may cause release of methane, H_2S, dissolved organic carbon and various naturally occurring metals such as iron, manganese, and arsenic. The microbiology may also be impacted, not only by any introduced bacteria during biostimulation, but also by the changing biogeochemical conditions, or aggressive chemical conditions induced by chemical oxidation technologies. The goals of this research are to assess the controls upon secondary impact occurrence, to establish their longevity and to reduce impacts by more targeted remediation practice.

University of Birmingham The student will be part of the vibrant Water Sciences research group within the School of Geography, Earth & Environmental Sciences. They will be supervised by Dr Michael Rivett, a Senior Lecturer in Contaminant Hydrogeology with a significant track record of research in the contamination of groundwater by chlorinated solvents. *For further technical information or discussion, please contact* ***Dr Michael Rivett*** *(**M.O.Rivett@bham.ac.uk**)*

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British Geological Survey (BGS) The student will have opportunity to link with the BGS based at Keyworth in the application of geophysical methods to Geosyntec's investigation / remediation sites.

[1]White, R.A., Rivett, M.O., Tellam, J.H., 2008. Paleo-roothole facilitated transport of aromatic hydrocarbons through a Holocene clay bed. *Environmental Science & Technology*, 42, 7118-7124.