Institution: University of Sheffield

Unit of Assessment: 14 - Civil and Construction Engineering

Title of case study: Changing policy and practice for contaminated land and groundwater

1. Summary of the impact

Our research on the natural processes that reduce pollutant concentrations in the subsurface has enabled the UK to adopt "Natural Attenuation" as a management policy and has changed professional practice at many contaminated sites. The massively reduced costs of this approach over active clean-up of sites in 2008-13 has saved a minimum of £100M for the UK. Our research has also influenced European practice, saving hundreds of millions of Euros. The beneficiaries are typically chemical industries of all sizes, from refineries to small repackaging plants and petrol station owners, but also local authorities and the State in cases where they would bear the cost of clean-up.

2. Underpinning research

From 1999-2009, the University of Sheffield's Groundwater Protection and Restoration Group conducted the UK's largest research programme on natural attenuation, working with complex pollutant mixtures dissolved in groundwater on contaminated sites in consolidated rock aquifers.

Natural attenuation is the combination of physical, chemical and biological processes which reduce pollutant concentrations. In the UK alone, there are over 100,000 sites polluted by organic chemicals which pose environmental and health risks. Because of the complexities of working in the subsurface, the typical cost of an active clean-up is £500,000; the situation in the rest of the world is similar or worse. If we can reliably predict that Natural Attenuation will reduce pollutant concentrations enough, active clean-ups and the associated costs can be avoided, reducing businesses' liabilities and increasing the value of their land holdings. Our research has enabled the Environment Agency to formally adopt Natural Attenuation as an acceptable risk management approach, saving significant national resources; the revolution is to not try and remove all the pollution as was being done in the USA in the multi-billion dollar approach under the Superfund programme, but to recognise that natural processes can predictably reduce risk once these processes can be defined and quantified.

Supported by successive EPSRC Platform Grants (1999-2004, 2004-09) and funding from EPSRC, NERC, Environment Agency, BBSRC, EU and industry, and using a combination of field investigation, laboratory experimentation and numerical modelling, we investigated the processes that occur in groundwater pollution plumes containing high concentrations of multiple pollutants. We described the multiple, spatially variable, biodegradation processes, created a conceptual model of the geochemistry and microbiology of these processes [R1], validated this through laboratory experiments and numerical modelling [R2] and developed theoretical frameworks to interpret these at different scales [R3]. We showed that biogeochemical gradients at the fringes of pollution plumes provide a range of conditions in which rapid biodegradation occurs, and thereby demonstrated that solute transport by transverse dispersion is often the key factor in controlling plume length [R4]. These results led to simple quantitative tools (the 'fringe and core' concept, and the 'electron-balance model') suitable for analysis of sites without the same quantity of data as our research sites [R5, R6].

The Sheffield researchers in the papers cited are Dr Steven Thornton (1998-), Prof David Lerner (1998-), Prof Steven Banwart (1998-), Prof Bob Watkinson (Visiting Professor, funded by Shell Research, 1998-2003), Dr Colin Smith (1998-), Dr Roger Crouch, 1999-2004), Dr Wei Huang (PhD student to 2002, Lecturer and Senior Lecturer 2008-), Dr Michael Spence (PDRA 2001-2005, joined Shell in 2005), Sasha Oswald (PDRA 2000-2004, now at University of Liepzig), M. Gutierrez-Neri, Ian Watson, and Sean Quiqley (research students).

Some projects were collaborations with other research organisations including, for the work cited: Leeds University (isotope measurements and nitrate and sulphate degradation experiments); Institute for Freshwater Ecology (now CEH, Lancaster; environmental microbiology, identifying bacteria and their activity in field samples); British Geological Survey (supporting field sampling); Universities of Alabama Waterloo (numerical modelling of one site and a lab experiment), and Utrecht University (mathematical analysis). Our collaborators provided techniques to support laboratory experiments and field sampling and analysis, numerical modelling software and confirmatory modelling of our hypotheses, and co-supervision of some students. All of the research projects were conceived and led by academics at Sheffield, who also developed the primary hypotheses, overall interpretations of sites, and the quantitative tools.

3. References to the research [**denotes best indicators of quality of underpinning research]

[R1] **S.F. Thornton, S. Quigley, M. Spence, S.A. Banwart, S. Bottrell and D.N. Lerner, 2001. Processes controlling the distribution and natural attenuation of dissolved phenolic compounds in a deep sandstone aquifer. *J. Contaminant Hydrology*, 53, 233-267. doi: 10.1016/S0169-7722(01)00168-1

[R2] U. Mayer, S. Benner, E. Frind, S.F. Thornton, and D.N. Lerner, 2001. Reactive transport modeling of processes controlling the distribution and natural attenuation of phenolic compounds in a deep sandstone aquifer. Journal of Contaminant Hydrology, 53, 341-368. doi: 10.1016/S0169-7722(01)00173-5

[R3] **Watson, I.A., Oswald, S.E., Banwart, S.A., Crouch, R.S., and Thornton, S.F. (2005) Modelling the dynamics of fermentation and respiratory processes in a groundwater plume of phenolic contaminants interpreted from laboratory- to field-scale. *Environmental Science & Technology*, 39, 8829-8839. doi: 10.1021/es0507970

[R4] W.E. Huang, S.E. Oswald, D.N. Lerner, C.C. Smith, and C. Zheng, 2003. Dissolved oxygen imaging in a porous medium to investigate biodegradation in a plume with limited electron acceptor supply. *Environmental Science and Technology*, 37(9), 1905-1911. doi: 10.1021/es020128b

[R5] M. Gutierrez-Neri, P.A.S Ham, R.J. Schotting and D.N.Lerner, 2009. Analytical modelling of fringe and core biodegradation in groundwater plumes. *J. Contaminant Hydrology*, 107, 1-9. doi: 10.1016/j.jconhyd.2009.02.007

[R6] **S.F. Thornton, D.N. Lerner and S.A. Banwart, 2001. Assessing the natural attenuation of organic contaminants in aquifers using plume-scale electron and carbon balances: Model development with analysis of uncertainty and parameter sensitivity. *J. Contaminant Hydrology*, 53, 199-232. doi: 10.1016/S0169-7722(01)00167-X

4. Details of the impact

Knowledge exchange, that is close working with end-users, has always been a core principle of our research team and is the process that has led to the impacts described below. We work with real sites and use science to address complex practical problems. We have developed close relationships with industry and the regulator (the Environment Agency) including, for example, Visiting Professors and secondments from Shell, Environment Agency, and consultancies such as AEAT and Sirius. With these partners, we created and led an EPSRC-funded *Network on Natural Attenuation in Groundwater and Soils (NNAGS*; 1998-2001*),* which led to policy documents, economic impacts and training [see quote from S1 below].

Four inter-related types of impact are described here: (1) changes in professional practices, (2) creation and application of national policy, (3) national and site-specific economic impacts, and (4) influencing European industrial practice.

(1) **Changes in UK professional practice.** The Environment Agency funded a Fellowship for Thornton to work on natural attenuation research, policy development and training (1999-2003). During the Fellowship, he helped create their guidance document (see below) and delivered 20 training events to over 200 staff across the UK. Since then, we have delivered virtually all the professional training on Natural Attenuation in the UK, giving 24 CPD courses on Natural Attenuation and Risk Assessment, and including specialist modules in our Contaminant Hydrogeology MSc. From 1999-2013 we have trained ~100 students and ~300 CPD delegates in these fields. We also gave 3 courses in China to ~100 delegates, and inspired the inclusion in a Chinese textbook of a major section (1/8 of book) on natural attenuation; the book has already had 26 printings [S5].

(2) **Creation and application of national policy.** We used our research to help write two new policy documents in 2000, which remain in force. They enable and encourage the appropriate use of Natural Attenuation as a management strategy for contaminated land through the use of science-based investigation, assessment and monitoring of field sites. The Environment Agency says:

> *"With regard to research into natural attenuation (NA) of pollutants and development of practice in the use of monitored natural attenuation (MNA) as a remediation option it seems undeniable that the University of Sheffield played a pivotal role in the UK. The strong links that were made between Sheffield and the Environment Agency (and other regulators), industry (small and large) and indeed research groups in other academic institutions played a major part in this.*
>
> *Your work at Four Ashes on the biodegradation of phenol and related compounds was instrumental in getting Environment Agency buy-in to the idea of natural attenuation as a serious component of site management. The outputs from that work* [examples given above, R1, R2, R3, R5, R6] *and the subsequent network NNAGS led to a range of Agency guidance and policy documents, most obviously the R&D Publication 95 "Guidance on the Assessment and Monitoring of Natural Attenuation of Contaminants in Groundwater". This in turn influenced our strategic "Policy and Practice for the Protection of Groundwater" that sets out Agency thinking on groundwater protection. Both of these documents are widely used, within the Agency on a daily basis and by our customers in industry to understand our regulatory needs. R&D Publication 95 has stood the test of time and I estimate it helps to inform remediation decisions on dozens of sites per year at the current time."* [S1].

(3) **Site-specific and national economic impacts.** Financial information on individual sites is difficult to obtain due to commercial confidentiality. However we are able to present information from one of our research sites, from one major land owner, and a national survey, as follows:

- At Site A, where many research projects were based, the owners are prepared to give information on the multi-part clean-up operation they implemented in 2009. The design drew significantly on our research-based understanding of the inhibiting effects of contaminant toxicity on biodegradation in the aquifer [R1, R2, R3, R5] and our research-based assessment that natural attenuation would only occur satisfactorily under specific conditions. This design has saved £1M per year between 2009-2013, compared with the cost of the alternative full pump and treat operation [S3].
- An owner of 50 large problem sites has stated that Natural Attenuation plays a significant role in reducing risk and remediating 11 of the 14 sites where it is taking action. It has analysed the cost-benefit of Monitored Natural Attenuation in comparison to more aggressive remediation on 3 of these sites and found that the cost avoided is at least £20M [S2].
- CL:AIRE, the industry's knowledge exchange group, estimates that Monitored Natural Attenuation was formally adopted for about 3% of site remediations in 2008-12. Through a survey of consultants active in contaminated land and groundwater, CL:AIRE derives very

conservative estimates for the period 2008-12 that Natural Attenuation was adopted as the remedial strategy on at least 120 sites per year, with a typical saving of £166k per site, i.e. a total saving of at least £100M since 2008 [S2].

(4) **Influencing European industrial practice.** CONCAWE, the association of almost all the oil refining companies in the EU, Norway and Switzerland, has stated "*… research on monitored natural attenuation undertaken at Sheffield University over the past decade has had a significant beneficial impact on industry good practice issued by CONCAWE, and on the practices of its member companies. … In financial terms alone, the cost savings to our industry in Europe associated with the use of MNA solutions instead of intensively engineered solutions, is probably in the order of hundreds of millions Euros during the period 2008 to 2012*" [S4].

Overall, the policy and practice changes that resulted from our research have led in the census period to:

1. Savings of typically £166K per site, and up to several million pounds on large and complex sites
2. A total saving in the UK of at least £100M
3. Savings in Europe in the oil sector alone of several hundred million Euros.

5. Sources to corroborate the impact

S1. Emailed letter from: Theme Expert (Air, Land and Water Research), Evidence Directorate, Environment Agency.

S2. The Project Director of CL:AIRE (Contaminated Land: Applications in Real Environments, a knowledge exchange forum between government, regulators, researchers, land-holders and consultants), will confirm the anonymous data from the large site owner and the size of the UK geo-environmental market, the share using MNA and its value.

S3. The UK Director of Operations of the owner of Site A will confirm that the design of the remediation draws on Sheffield's research and has led to an estimated saving of £1M/year.

S4. Letter from Technical Coordinator (Water, Soil, Waste, Safety and Oil Pipelines), CONCAWE. Corroborates the environmental impact of our research.

S5. Head of Environmental Engineering, Tsinghua University, Beijing can confirm evidence relating to China.