The Economics of Remediating NAPLs in Fractured Aquifers

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Abstract

When present in complex fractured aquifers, NAPL contamination is especially problematic, not only in terms of detection and prediction of future behavior, but with respect to remediation. Rock fracture networks are typically highly heterogeneous and difficult to characterize, and NAPL behavior within these networks does not fit commonly-used porous medium models. DNAPLs may penetrate to considerable depths in fractured systems, invading increasingly smaller aperture features as NAPL heads build with depth. LNAPLs may also penetrate beneath the groundwater surface in near-vertical fractures, and may migrate laterally from source both up- and cross-gradient, depending on fracture network geometry. These characteristics, combined with the complexities inherent in multi-phase flow, typically make remediation of NAPL in fractured systems difficult (if not in some cases practically infeasible) and expensive. Traditional NAPL removal methods (such as focused pumping and high-vacuum extraction), employed with some degree of success in unconsolidated aquifers, have generally performed poorly in fractured systems. Promising new techniques for NAPL removal, such as steam-assisted recovery, and surfactant enhanced aquifer remediation (SEAR), have yet to be applied rigorously in fractured systems. Economic analysis can be used to compare the costs of NAPL remediation with the benefits that are expected to result from that remediation. Decisions on the required level of remediation can thus be made with an understanding of the full economic ramifications, including the wider implications for the environment and society. Benefits of remediation include those that accrue to the problem holder (such as increase in land value), and those that are produced for the rest of society (often described as the value of damage avoided by taking action). Wider (external) benefits can include the value of damage avoided to the aquifer as a productive resource, and as it contributes to the maintenance of ecosystems and surface water resources. By explicitly placing monetary values on each of the expected benefits of a particular remedial option, they can be compared like for like with the costs of implementing that action. Thus, various possible remedial alternatives can be compared to determine which provides the most benefit to society as a whole, and all stakeholder's concerns can be represented and compared in an equal unit of measure – money. Economic analysis can also be used to identify situations in which a technical impracticability (TI) waiver may be advantageous for society. Two examples are provided where NAPL exists in fractured aquifers. Comparison of the costs and benefits of aquifer remediation illustrates the conditions under which application of more aggressive remedial techniques are warranted, and where they are not. In general, active remediation may be beneficial and warranted if aquifer use value is high, if alternative water sources are scarce, and if an important non-use value is

threatened (such as groundwater recharging a sensitive and valued wetland ecosystem). In many cases, the anticipated benefits of NAPL remediation in a fractured aquifer will not justify the level of expenditure required to realize those benefits, with currently available technology. To allow benefits to be more accurately quantified, studies are required on valuing aquifers, both in the USA and Europe. It is also clear that continued research is needed to develop remedial techniques for fractured systems which are more effective and less costly.

INTRODUCTION

The problems associated with NAPLs (non-aqueous phase liquids) in fractured aquifers have received significant attention in the technical literature over the last decade (Mackay and Cherry, 1989; Mercer and Cohen, 1990; Pankow and Cherry, 1996). Concerns over the impacts of chlorinated solvents on groundwater have led to a significant body of work examining DNAPLs in the subsurface, including in fractured rocks (Cohen and Mercer, 1993; Kueper and McWhorter, 1991). More recently, the unique behavior and problems associated with LNAPLs in fractured aquifers have been studied (Hardisty *et al,* 1998; Wealthall *et al,* 2002; Hardisty *et al*, 2004). The highly heterogeneous nature of fractured systems, combined with the inherent complexity of multiphase flow, typically make characterization and remediation of NAPL in fractured systems difficult and expensive.

As remedial costs rise, there is an increasing need to understand the justification for spending. Economists will typically examine the costs of a project against the benefits which accrue to all of society by the implementation of that project. Hardisty and Ozdemiroglu (2005) have examined the application of cost-benefit analysis to problems of groundwater remediation. Until recently, relatively little research has been conducted into applying rigorous cost-benefit techniques to problems of groundwater remediation and protection. Most of the technical-scientific literature on the subject focuses largely on the application of specific techniques and technologies to groundwater problems, and deals almost entirely with remedial costs, cost-comparisons, and cost-effectiveness. The wider benefits of remediation are rarely discussed (Peramaki and Donavan, 2003; Goist and Richardson, 2003). Much of this work is primarily of interest to problem holders, but even so, very little is available which discusses the private benefits of remediation that accrue to problem holders.

REMEDIATION OF NAPL IN FRACTURED ROCK

Remediation of LNAPL and DNAPL in fractured aquifers is a complex undertaking. DNAPLs may migrate to significant depths via fractures, and if spill volumes are large and fracture interconnectivity high, DNAPL may invade progressively smaller aperture fractures with depth (Kueper and McWhorter, 1991). As NAPL fluid pressures increase, matrix invasion may also occur. The vertical migration of LNAPL in fractured aquifers is constrained by the water table, but despite this, significant penetration beneath the water table may occur, and lateral migration may occur in directions independent of the hydraulic gradient (Hardisty et al, 1998). Within fractured aquifers, NAPL movement is governed by the geometry of the fracture network (including fracture orientations, densities, interconnectivity, apertures and wall roughness), capillary pressure and fluid saturation relationships, and the properties of the NAPL (density, interfacial tension, viscosity).

Whether dealing with LNAPL, N-NAPL (neutral-buoyancy NAPLs), or DNAPL, significant challenges exist when contemplating remediation. First, characterization of the distribution and behavior of NAPLs in fractured rock is notoriously difficult (CL:AIRE, 2002; Hardisty et al, 2004; Pankow and Cherry, 1996). In a deterministic approach, fracture networks need to be characterized, major fracture sets identified in the field, and representative fracture parameters determined. The occurrence of NAPL within these fractures then needs to be ascertained, areally and vertically. For DNAPLs, definitive characterization to depth may be problematic (Guswa et al, 2001; Lane et al, 2000, Cohen and Mercer, 1993, Pankow and Cherry, 1996). Rarely in practice is a complete characterization feasible. Next, proven techniques for NAPL removal from fractures are few. Pump-and-treat methods, while effective for containment, have proven disappointing for NAPL removal, even when coupled with targeted NAPL recovery pumping and skimming (Schmelling and Ross, 1989). Recently, more aggressive in-situ NAPL-removal methods have been field tested, including high vacuum extraction, thermal heating, and surfactant assisted aquifer remediation (Taylor et al, 2001). These relatively expensive methods have shown good results in some cases, but have not yet been rigorously tested in fractured rock environments. Finally, when the understanding of contaminant distribution is sketchy, even the simplest remediation techniques can prove unsuccessful. The combination of new or unproven remedial techniques, incomplete characterization, and complex aquifer and contaminant distribution conditions, makes remediation success uncertain, and costs high. Within this context, a clear understanding of the financial and broader economic implications of remediation provides decision makers with the means to select achievable and ultimately valuable remedial objectives.

THE ECONOMICS OF GROUNDWATER REMEDIATION

An economic model for considering the costs and benefits of remediation is presented in Hardisty and Ozdemiroglu (2005). The main variables in the analysis are the timing of remedial action, and the spatial context and scope of the action. So, preventive action could be taken now, thus avoiding future damage, or can be postponed allowing existing damages to continue, and possibly also allowing future damages to occur. The other variable is spatial - the location at which the avoidance or remediation takes place.

The Benefits of Remediation

In economic terms, the benefits of remediation are defined as increases in overall human welfare resulting from remedial action. These benefits are monetized (expressed in units of money). Benefits of remediation can be expressed as the “damages avoided” by undertaking that action. Baseline damages can be expressed as a function of time, depending on the nature of the contaminant, speed of movement, assets at risk and the economic value of those assets.

Risk assessment is often used to quantify the expected impacts on identified receptors, should the remediation not occur. If these impacts are avoided, wholly or partially, by successful implementation of the remediation, economic benefits may result. These economic benefits could accrue by virtue of the protection of the value of groundwater as an input to production or potable supply (direct use value), its role in the functioning of ecosystems (indirect use value), or its potential future uses (option value). People may also value groundwater and be willing to pay for its protection for reasons unrelated to their use of groundwater (non-use values), because of its benefits to others (altruistic value), for future generations (bequest value), and for its own sake (existence value). The sum of these different types of economic benefits or values is referred to as Total Economic Value (TEV).

Remedial benefits which may accrue to the problem holder include increased property value, elimination of corporate financial environmental liability, avoidance of negative public relations or even impact on company stock value, protection of a resource used as a key input to an economic process, and avoidance of exposure of on-site personnel to pollutants. A full economic analysis also considers benefits that accrue to society as a whole. These are known as ‘external’ benefits, so long as they are not compensated by or paid for to the problem holder. These can include increases in value to neighboring sites (which can be used as a measure of the benefits to local people, including possibly health benefits), recreational benefits to local residents (insofar as these are not captured in the change in property values), and avoidance of ecological damage (if not otherwise captured in recreational or property value increase).

In computing the benefits of remediation, care must be exercised to avoid “double counting” of some benefits, and of ensuring that transfer payments are not included. Transfer payments do not cause a net change to the costs and benefits to society as a whole, but simply transfer funds from one party to another within society. For example, litigation expenses or value of bad publicity are transfer payments. The problem holder’s costs for litigation become the benefits of the law firm, and hence cancel each other out when a full social analysis is undertaken.

In practice, only some remedial benefits can be readily quantified and monetized. These are likely to include several of the key private benefits (such as land value, and economic input values). External benefits are less readily monetized. The degree to which monetization of benefits occurs depends on the circumstances. For more complex, high profile, and serious problems, such as NAPLs in fractured aquifers, a greater degree of analysis may be warranted. In these cases, economic techniques are available to estimate other non-use benefits.

Of all the monetization techniques available, perhaps the most robust and readily available is the hedonic pricing technique using property values. When a contaminated site is remediated, it is not only the site owner who benefits. By removing what might have been a potentially hazardous condition, the whole neighborhood benefits. Several recent studies have shown that people and businesses perceive a real economic benefit when a neighboring waste site or polluted site is remediated (DEFRA, 2003). This is due to the removal of blight or dis-amenity from the properties in the vicinity of the remediated site. People would rather live in an area without contamination and waste, if they had the choice, and this preference shows itself in the (higher) prices of properties in cleaner areas

In practical terms, in situations where only easily-monetized values are considered, the benefits of remediation could be considerably under-estimated.

Cost-Benefit Analysis

Remedial objective setting must consider the benefits of achieving a given objective. In economics, the overall objective of any decision is assumed to be the maximization of human welfare over time. To compare the different benefit and cost streams over time, the process of discounting is used and amounts over time are expressed as present values. Economic analysis recommends the decision with the maximum Net Present Value (NPV) (present value of net benefits, or benefits minus costs, over time) or the highest Benefit Cost Ratio (BCR) (ratio of the present value of benefits to the present value of costs).

What is important in a decision making process is the overall comparison of the costs of remediation with the benefits of remediation; hence the term ‘cost-benefit’ analysis. Remediation costs will tend to vary with size of plume, type of contaminants, and the nature of the geologic and aquifer material and properties. So at least in some cases, the later we intervene, the higher the cost of remediation (C_r) will be. C_r includes all of the costs which lead to the implementation and successful conclusion of the remediation. Sometimes, remedial activities will also lead to secondary impacts to the environment (such as the release of contaminant vapors to atmosphere). The burden of these impacts is borne by society, and thus the value of the damages associated with these impacts are called “external costs of remediation”, or C_x (Hardisty and Ozdemiroglu, 2005).

The cost-benefit analysis simply compares the overall benefits of remediation to the overall costs, resulting in a net benefit. To find net benefits, we deduct the flow of costs incurred to undertake the remediation from the flow of benefits resulting from the remediation. Thus, the present value of the net benefits (or the net present value (NPV)) of the selected remediation policy is given by:

$$NPV = \sum_{0}^{t} \left[\frac{B_r - (C_r + C_x)}{(1+i)^t} \right]$$

Where B_r are the benefits of remediation, usually expressed as the value of the damage that would be avoided if action is taken, *t* is the planning horizon (or period of time over which the analysis is being conducted), and *i* is the discount rate.

EXAMPLE: N-NAPL in a Fractured Aquifer, UK

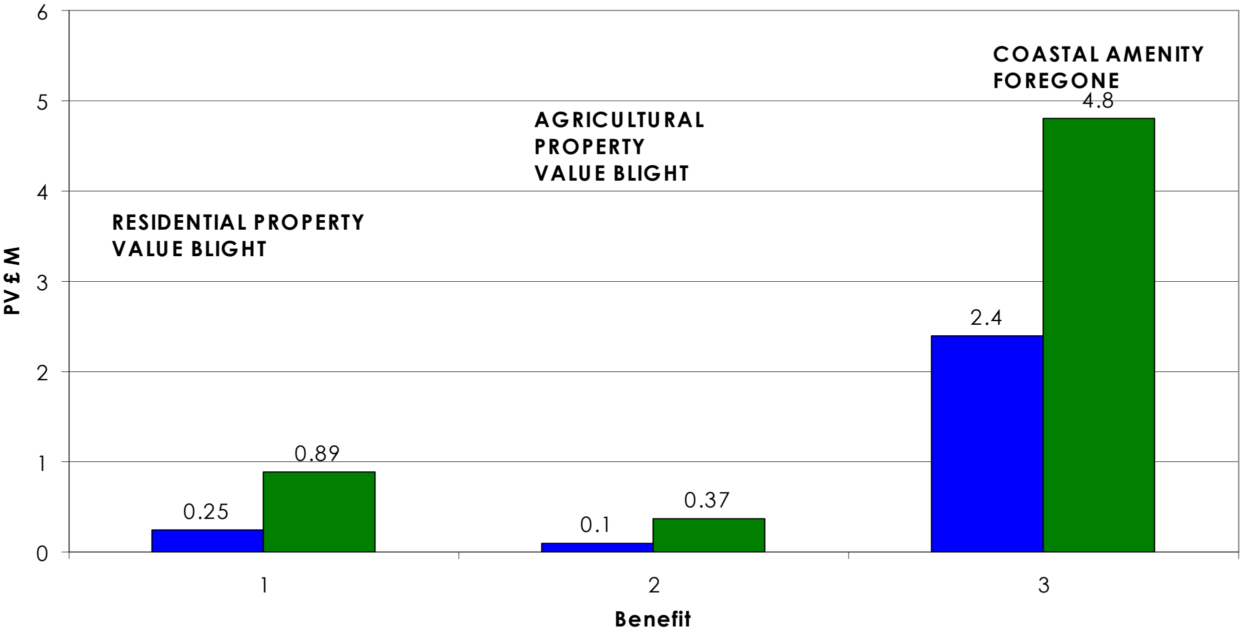
Background

A disused MGP (manufactured gas plant) facility in the UK has resulted in significant contamination of the subsurface by coal tar compounds, including NAPLs. The site lies in the commercial centre of a busy town, adjacent a high-value residential neighborhood. The uppermost coarse-grained saturated gravel deposits are extensively contaminated by NAPL, which is very close to neutral density (N-NAPL). Groundwater occurs at a depth of about 5 m across the site. Some of the NAPL has penetrated into the underlying fractured carbonate aquifer to depths of up to 15 m below ground level. The aquifer is extensively used throughout the region for public water supply (PWS), and an operating PWS well lies approximately 2 km down-gradient of the site. Trace levels of MGP contaminants have been detected in this PWS well.

Benefits

A simple analysis reveals a few readily-monetizable benefits of remediation: 1) the value of the property itself (approximately $ 7.0 M (million)); 2) increased property value realized by neighbors (200 residential properties and 100 residential apartments situated within 0.5 km of the site (DEFRA, 2003); 3) the value of the aquifer being damaged, represented by the commercial water production volume per annum which is impacted by contaminants from the site, multiplied by the unit cost of treatment to render that production fit for sale. The PWS is pumping 5.8 Mm3/yr, and treatment costs approximately $0.05/m^3, and 4) the value of the river which is being impacted to a small degree by contaminants migrating through the gravels, estimated at $0.01M / year.

The analysis is completed using a planning horizon of 20 years, and a discount rate of 3.5%, which is the current published UK Treasury rate for social discounting. The blight factor on property is set at 5 % (DEFRA, 2003) .



A summary of the benefits which may be realized as a result of remediation at the site is provided in Table 1. If all benefit categories could be realized, total benefits would be approximately $15.1M. However, not all benefit categories will be realized by each remedial approach, as shown below.

Table 1. Benefits Summary

BENEFIT CATEGORY	Sum of Benefits over 20 yrs ($M)
Property value	7.0
Reduction in Blight in Neighborhood	3.87
Aquifer protection	4.12
River Protection	0.14
TOTAL POSSIBLE BENEFITS	15.13

Remedial Approach Options

A number of alternative remediation approaches are considered, each designed to achieve specific remedial objectives associated with management of the risks identified at the site. Remediation approaches considered for the site are 1) source removal by excavation of shallow sediments (with on-site treatment), and in-situ treatment of NAPL in fractured rock through a combination of pumping, water flushing and in-situ chemical oxidation; 2) partial excavation of key hot-spots, with no attempt to remediate fractured bedrock beneath the site; 3) containment of dissolved phase contamination in the fractured aquifer through pump-and-treat, to prevent additional migration of contaminants off-site and to the PWS, and 4) monitored natural attenuation, which essentially is maintenance of the status quo, no active remediation, but with investment in a program of monitoring over the next 20 years.

Cost Benefit Analysis

Table 2 compares the costs, benefits, and the BCR for each remedial approach. BCR's greater than 1.0 indicate that the benefits of the remediation /objective approach exceed the costs, and thus it is economically worthwhile to implement. The higher the BCR, the greater the benefit to society.

Table 2 - Benefit-Cost Ratios

REMEDIATION APPROACH	PV COST ($M)	PV BENEFIT ($M)	NET BENEFIT ($M)	BCR
1	8.47	14.1	5.6	1.65
2	4.67	8.2	3.5	1.74
3	3.85	4.1	0.3	1.07
4	1.93	0.4	-1.5	0.22

Table 2 shows that three of the four remedial approaches considered result in a net overall economic benefit. The benefit cost ratio is highest for approach 2 (BCR= 1.74; partial excavation only), and approach 1 (full excavation and in-situ treatment; BCR=1.65). However, approach 2 accrues benefits largely from increase in property value, and does little to limit aquifer damage. Since it is a relatively low cost option, overall net benefits are high. However, approach 1 represents a much wider distribution of benefits, including substantial reductions in damage to the aquifer and PWS. The higher cost of this option is offset by the capture of these benefits, reflected by the highest net benefit ($5.6 M against $ 3.5 M for approach 2).

Containment of the plume (approach 3) would yield substantial aquifer benefits, but does not allow the property to be redeveloped, and is therefore only marginally economic (BCR=1.07). MNA, which is essentially the status quo, is not economic, since no substantial benefits are realized by any stakeholders, despite considerable expenditure.

Implications

In this simple example, the substantial cost involved in remediation of NAPL in the fractured aquifer, estimated at approximately $4 M, for this small site, is shown to be economic. The fact that the aquifer is an important source for a major PWS means that the benefits of remediating the aquifer justify this expenditure. If the value of water in this area was higher, then the remediation would be even more economic, to the point where additional expenditure could be justified, for a heightened level of protection.

In this example, MNA is the cheapest of the options, but also the most uneconomic. This illustrates a common finding in CBA for remediation – that cheapest is not always most economic. In a purely financial analysis (ie from the perspective of the problem holder only), least cost remedial solutions are usually favored. However, by not accounting for the wider benefits of remediation, an important part of the picture is missed.

EXAMPLE - DNAPL in a Fractured Aquifer - USA

Background

A small site in the Midwest of the USA was used since the 1950's in the recycling of transformers. Until the 1980's when the site was closed, a variety of chlorinated solvents were disposed of at the site in shallow unlined trenches. The site is situated on a small hill, on the outskirts of a small rural town. Down-gradient of the site are fields, a small wetland and a creek. DNAPL soaked into the over 8 m of fine-grained sediment cover at the site, and in places reached the highly weathered top of the fractured carbonate aquifer below. The groundwater surface at the site is within the bedrock aquifer, at about 12 m below ground. The aquifer itself is characterized by low yields and marginal quality from a drinking water perspective. An extensive remediation program resulted in the on-site thermal treatment of over 20,000 m^3 of NAPL-contaminated soil, removing the vast majority of the NAPL on-site. Subsequent groundwater monitoring revealed low concentrations of certain chlorinated solvents moving off-site within the fractured bedrock aquifer, towards the wetland and creek. Small amounts of DNAPL are likely present in selected fractures within the bedrock at the site, perhaps as residual ganglia, or as adsorbed phase within sediment-filled fractures. However, the complexity of the fracture regime at the site makes detailed characterization of the nature and occurrence of NAPL difficult, and no direct evidence of NAPL in fractures has been found. Even dissolved phase concentrations of contaminants may or may not be present in selected fractures a few meters apart.

Benefits

A simple analysis identifies the following benefits which may accrue from remediation at the site: 1) increase in property value at the site itself. The area is rural, and land values in the area are relatively low. Clean, the site is worth about $ 0.25 M; 2) uplift in the value of surrounding properties through removal of blight. Within a 2 mile radius, the sum of property values is estimated at $ 3M by area realtors. Applying a 10% blight factor, remediation of the site would result in a benefit of $ 0.3 M; 3) prevention of aquifer damage. Using simple modeling, the presence of the dissolved phase plume at the site effectively eliminates about 800,000 m^3/yr of potential abstraction (even though the aquifer is used only sparsely in the area, and not at all for public supply). At 5% discount rate over 20 years, and assuming a brut value for water of $0.1/$m^3$, this equates to about $ 1.0 M in lost aquifer potential; and 4) value of the wetland, to which dissolved phase contaminants may flow. Given the low concentrations expected under worse case conditions, a nominal 20 year value of $ 0.1 M is assigned. Table 3 provides a summary of the possible benefits of remediation.

Table 3. Benefits Summary

BENEFIT CATEGORY	Sum of Benefits over 20 yrs ($M)
Property value	0.25
Reduction in Blight in Neighborhood	0.6
Aquifer protection	1.0
Wetland Protection	0.1
TOTAL POSSIBLE BENEFITS	1.95

Remedial Approach Options

Recognizing the difficulties involved in remediating low levels of dissolved phase, and possible small concentrations of residual DNAPL (which could not be located), in the complex fractured rock environment, three main remedial approach options were identified as part of the evaluation process: 1) soil remediation (already completed), with MNA (monitored natural attenuation) for groundwater over 20 years; 2) soil remediation (already completed), with in-situ treatment of identifiable hotspots in groundwater, and 20 years of MNA; and 3) soil remediation (already completed), with groundwater pump-and-treat to contain and reduce the mass of the dissolved phase plume.

Cost-Benefit Analysis

The costs and benefits of each of the three remedial options being examined are provided in Table 4. The analysis is being done after the soil remediation was already completed, and so the costs of soil remediation are included in each option. Nevertheless, none of the options is shown to be economic - that is resulting in a net increase in welfare for society. The combination of low property values (small benefits), and a complex and difficult to characterize and remediate aquifer (high costs), produces BCR's below unity. Even if the economic value of the aquifer were increased, by increasing the brut value of water from \$ 0.1/m^3 to \$ 1.0/m^3, the costs of remediation are so high that all of the options remain uneconomic.

Table 4 - Benefit-Cost Ratios

REMEDIATION APPROACH	PV COST ($M)	PV BENEFIT ($M)	NET BENEFIT (£M)	BCR
1	3.5	0.90	-2.60	0.26
2	8.7	1.01	- 7.69	0.12
3	12.9	1.62	- 11.28	0.13

Implications

In this case, all options are uneconomic. The high cost of remedy for NAPL in fractured rock cannot be justified by the benefits which society will gain as a result of action. In this case, a technical impracticability (TI) waiver would be both technically and economically justified, leading to selection of remedial approach 1.

DISCUSSION

In the first of these simple illustrative examples (the MGP site in the UK), high urban property values combined with impacts on a major aquifer, used by an important nearby PWS, mean that remediation of NAPL in fractured rock, although very expensive, is economic. Society as whole is better off as a result of remediation taking place. In contrast, in the second example, situated in rural USA atop a low-yield and little-used aquifer, remediation of NAPL in the fractured aquifer is not economic. In both cases, active remediation of NAPL in complex and highly heterogeneous fractured rock is very expensive (over $ 4 M and almost $10 M respectively). However, the economics of the two cases are very different.

In general, active remediation may be beneficial and warranted if aquifer use value is high, if alternative water sources are scarce, and if an important non-use value is threatened (such as groundwater recharging a sensitive and valued wetland ecosystem). In many cases, the anticipated benefits of NAPL remediation in a fractured aquifer will not justify the level of expenditure required to realize those benefits, with currently available technology. To allow benefits to be more accurately quantified, studies are required on valuing aquifers, both in the USA and Europe. It is also clear that continued research is needed to develop remedial techniques for fractured systems which are more effective and less costly.

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Biographical Sketches

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Paul received a BSc in Geological Engineering from University of British Columbia, Canada, an MSc in Engineering Hydrology from Imperial College of Science and Technology, London, and a PhD in Environmental Engineering from the University of London, UK, where his thesis focused on the behavior of LNAPLs in fractured rock. He is a founding partner of Komex Environmental Ltd., a global environmental consultancy, and is currently Managing Director of International Operations for Komex. His interests include characterization and remediation of complex and fractured contaminated sites, and the economics of groundwater protection and remediation. Paul is Visiting Professor in Contaminant Hydrology at Imperial College, University of London. With Ece Ozdemiroglu, he is co-author of a new book entitled “The Economics of Groundwater Remediation and Protection”, published by CRC Press.

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Ece is the founding director of Eftec Ltd, a consultancy specializing in environmental economics. She obtained an MSc in environmental economics and natural resource management from University College London. She has 12 years of experience in environmental economics, and has worked on cost-benefit analyses for a variety of clients world-wide. With Paul Hardisty, she is the co-author of a new book on the economics of groundwater remediation.