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Research article

Sustainability assessment of electrokinetic bioremediation compared with alternative remediation options for a petroleum release site

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ABSTRACT

Sustainable management practices can be applied to the remediation of contaminated land to maximise the economic, environmental and social benefits of the process. The Sustainable Remediation Forum UK (SuRF-UK) have developed a framework to support the implementation of sustainable practices within contaminated land management and decision making. This study applies the framework, including qualitative (Tier 1) and semi-quantitative (Tier 2) sustainability assessments, to a complex site where the principal contaminant source is unleaded gasoline, giving rise to a dissolved phase BTEX and MTBE plume. The pathway is groundwater migration through a chalk aquifer and the receptor is a water supply borehole. A hydraulic containment system (HCS) has been installed to manage the MTBE plume migration. The options considered to remediate the MTBE source include monitored natural attenuation (MNA), air sparging/soil vapour extraction (AS/SVE), pump and treat (PT) and electrokinetic-enhanced bioremediation (EK-BIO). A sustainability indictor set from the SuRF-UK framework, including priority indicator categories selected during a stakeholder engagement workshop, was used to frame the assessments. At Tier 1 the options are ranked based on qualitative supporting information, whereas in Tier 2 a multi-criteria analysis is applied. Furthermore, the multi-criteria analysis was refined for scenarios where photovoltaics (PVs) are included and amendments are excluded from the EK-BIO option. Overall, the analysis identified AS/SVE and EK-BIO as more sustainable remediation options at this site than either PT or MNA. The wider implications of this study include: (1) an appraisal of the management decision from each Tier of the assessment with the aim to highlight areas for time and cost savings for similar assessments in the future; (2) the observation that EK-BIO performed well against key indicator categories compared to the other intensive treatments; and (3) introducing methods to improve the sustainability of the EK-BIO treatment design (such as PVs) did not have a significant effect in this instance.

1. Introduction

The management of contaminated land is a global challenge. Its restoration is often considered to provide net positive benefits, but if remediation practices are selected and implemented poorly more environmental impact can arise than is associated with the contamination. Integrating sustainability practices into contaminated land remediation provides an opportunity for social, environmental and economic benefits of the process to be considered and optimised. Sustainable remediation is defined by the Sustainable Remediation Forum, UK (SuRF-UK) as “the practice of demonstrating, in terms of environmental, economic and social indicators, that the benefit of undertaking remediation is greater than its impact” (CL:AIRE, 2010). There are two ways in which sustainable remediation can be applied at contaminated sites (NICOLE, 2010): 1) at the management level, integrating sustainability assessments into the wider decision making process; and 2) at the site-specific level, by an assessment to compare options against certain sustainability indicators. SuRF-UK has produced a framework which provides a structure for implementing these two approaches within a contaminated site project. The framework has two stages: Stage A, plan and project design; and Stage B, remediation option appraisal and implementation. This study applied

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Stage B of the framework, by applying a sustainability assessment to contaminated site remediation technology selection.

The SuRF-UK sustainable remediation framework describes a tiered approach to sustainability assessments. There are three tiers, each requiring increasing amount of data for the assessment: Tier 1 is qualitative (e.g. simple rankings against ideal criteria); Tier 2 is semi-quantitative (e.g. multi-criteria analysis); and Tier 3 is quantitative (e.g. cost-benefit analysis). The steps associated with an assessment include (Bardos, 2014; Bardos et al., 2011): 1) defining remediation objectives to identify the decision that is being supported; 2) stakeholder engagement; 3) identifying boundaries of the assessment such as system, lifecycle, spatial and temporal; 4) identifying relevant sustainability indicators for the scope of the assessment; 5) defining the assessment methodology, i.e. either Tier 1, 2 or 3 or a combination; 6) conducting the sustainability assessment and 7) verifying and reporting the results.

Several case studies apply the SuRF-UK framework to contaminated sites and demonstrate the economic, environmental and social benefits of the process. For example, a Tier 1 assessment was applied to a fuel storage depot in Madeira, Portugal, concluding that enhanced bioremediation to be a more sustainable approach than thermal desorption, based largely on reduced cost and CO_2 emissions, but with an associated longer duration for remediation activity (CL:AIRE, 2013a). Additionally, Tier 2 and 3 assessments were completed at a former airbase site where aviation fuel was thought likely to impact a primary aquifer. It concluded that environmental and social impacts out-weighed the economic, resulting in a more expensive but more sustainable and operationally better solution (CL:AIRE, 2013b).

A novel aspect of this study is the inclusion of electrokinetic-enhanced bioremediation (EK-BIO) within risk management. Electrokinetics is the application of a direct current to the subsurface to initiate solute transport independent of hydraulic conductivity, by electroosmosis, electromigration and electrophoresis (Acar and Alshawabkeh, 1993). These transport processes can be used to enhance bioremediation at a range of scales (Gill et al., 2014). At the micro-scale, this can help increase bioavailability and bio-accessibility (Wick et al., 2007). At the macro-scale, electron acceptors and/or nutrients can be delivered into the contaminated zone to support biodegradation (Lohner et al., 2008). Furthermore, these transport processes can be as effective in heterogeneous sediments with significant hydraulic conductivity contrasts (Gill et al., 2015). The technology is considered a good candidate for sustainable remediation as the principal costs after set up are electricity and the amendment used (Alshawabkeh et al., 1999; Kim et al., 2014). Consequently, there is significant interest in coupling electrokinetics with other remediation technologies and incorporating it as part of remediation options appraisal will further advance the state of knowledge.

The aim of the study was to assess the sustainability of different remediation options, including the theoretical application of EK-BIO, for a gasoline/MTBE contaminated site. The objectives were to:

1. Perform Tier 1 and Tier 2 sustainability assessments on a site contaminated by an unleaded gasoline release from a petrol filling station and use the findings to inform a management decision;
2. Include EK-BIO in the remediation option appraisal, using an electron balance model to inform operational parameters such as treatment duration, power (electricity) consumption and amendment usage; and
3. Investigate the effect of incorporating photovoltaics and limiting amendment usage on the EK-BIO remediation option using different scenarios relative the base case above.

Currently there are no reported examples of using electrokinetic bioremediation within a sustainability assessment, or how modifications to the treatment design, such as inclusion of photovoltaics, influence the overall sustainability performance. These are important knowledge gaps in the development of electrokinetic remediation. Furthermore, this is the first peer-reviewed application of the SuRF-UK framework.

2. Conceptual site model

The focus of this study is a petrol filling station (PFS) site located up hydraulic gradient of a water supply well (WSW). There was a fuel release into the subsurface at the PFS resulting in the fuel additive methyl tert butyl ether (MTBE) detection in the WSW. The PFS was decommissioned, the fuel release stopped, and investigation and remediation undertaken. Several groundwater sampling and monitoring events have been completed at the site to assess the risk posed by MTBE to the WSW. Remedial action to date includes the installation of a hydraulic containment system (HCS) to break the source-pathway-receptor (SPR) linkage, and soil vapour extraction (SVE) and multi-phase extraction (MPE) to treat mobile and residual-phase LNAPL near the source zone.

2.1. Site geology and hydrogeology

The main hydrogeological units in the shallow subsurface at the site are summarised in Table 1 and a cross section in Fig. 1A. The top of the Cretaceous Chalk aquifer is located at around 20 m BGL, and forms a regionally important water supply aquifer. The Chalk is overlain by ca. 20 m low permeability clay till, through which a glacial sand channel was cut. The channel sands are a mix of high permeability sands and gravels interspersed with low permeability silt lenses. Regional groundwater flow is towards the north east, however, the local hydrogeological regime is modified by abstraction at the WSW, which draws Chalk groundwater in an easterly direction. When the WSW is on, groundwater flow in the channel sands and chalk is towards the well creating a downward vertical hydraulic gradient in the channel sands. When the WSW is not pumping the regional groundwater flow is dominant and the hydraulic gradient between the channel sands and chalk aquifer is reversed. The water table fluctuates under the influence of the abstraction and seasonal variations.

2.2. Contaminants of potential concern

Numerous petroleum hydrocarbon constituents are present on site. Those exceeding UK drinking water standard or World Health Organisation appearance taste and odour values at the highest number of locations include benzene, toluene, ethyl-benzene, xylene (BTEX) and MTBE. These compounds are considered the main contaminants of potential concern, consistent with other gasoline impacted sites (Bowers and Smith, 2014). Hydrocarbons were present in both free phase and dissolved phases. The free-phase has migrated south-east into the channel sands, with significant smearing due to groundwater fluctuation. The dissolved-phase within the channel sand is drawn down by the vertical

Table 1
Summary table of the geological units present on site.

Geological unit	Hydraulic conductivities (m s^{-1})
Channel Sands	1.5×10^{-5} to 1.2×10^{-9}
Glacial till	1.2×10^{-8} to 1.2×10^{-12}
Chalk	1.2×10^{-3} to 3.5×10^{-4}