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Life Cycle Assessment Combined with Performance Modeling for Assessment of the Environmental Impacts of Remedial Actions

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INTRODUCTION

Groundwater contamination by chlorinated solvents and hydrocarbon products represents a potential threat to our groundwater resources and surface water bodies. Contaminated sites are an important source for these compounds, which in subsurface environments exhibits a complex behavior and due to their high mobility can cause down-gradient contamination.

Risk assessment and remediation of contaminated sites have been undergoing considerable changes since the late 1970s, where groundwater contamination was recognized as a threat towards water resources. The reasons are related to at least two issues where previous expectations have not been met: (1) It has been recognized that the number of contaminated sites and the costs of remediating these sites are very large (EEA 2007); (2) The complexity of subsurface source zones is high and the timeframes for remediation are often very long (ITRC 2008).

This has initiated an increased focus on risk assessment and also a societal change in management of contaminated sites. It has been recognized that not all sites may need or can be cleaned up and that the risk associated with contaminated sites should be assessed by holistic approaches and that prioritization is needed (Troldborg et al. 2008; Lemming et al. 2010c). Furthermore, the needs for development of better, faster and "greener" remediation technologies for clean-up of soil and groundwater have been emphasized (US EPA 2008).

The typical risk from a contaminated site is associated with the use of the site (e.g. indoor climate, growing crops, and direct soil contact) or with leaching of contaminants to groundwater or surface water bodies. In terms of remediation the type of remedial actions are often different, although some remedial actions potentially can solve different types of risk.

SELECTION OF REMEDY AND LIFE CYCLE ASSESMENT

When it has been decided to remediate a contaminated site a screening of applicable technologies for remediating the site is typically conducted to evaluate the options and select the most appropriate one. In this selection process, a variety of aspects encompassing technical as well as environmental and economic considerations may be included (Grieger et al. 2010; Lemming 2010). Cost considerations, assessments of technical applicability and performance (clean-up levels, time frames) are important decision criteria. Moreover, other issues may be of high importance such as the annoyance experienced by people living at or near the

site. Excavation work may cause noise, dust and vibrations at the site, whereas *in situ* remediation may cause a smaller level of nuisance, but during a longer time period.

Recently, a holistic decision making process and the use of life cycle assessment for decision support for remedy selection has gained significant interest. A remediation technology removes a local contamination, but at the same time contributes to environmental impacts on the local, regional and global scale, due to the use of energy, chemicals and raw materials and the generation of emissions and waste. Such impacts from remediation may be termed *secondary impacts* to the environment as opposed to the *primary impacts* to the environment related to the on-site contamination.

Life cycle assessment (LCA) is a widely used decision support tool for environmental assessments. It is a quantitative method aimed at comparing environmental impacts related to fulfilling a defined function or service. LCA aggregates impacts occurring at all stages in the life cycle of the compared service, from raw material extraction, to production, use and final disposal. Because remediation may result in problem-shifting, LCA can be seen as an appropriate tool for environmental assessment due to its broad scope and systems perspective (Godin et al. 2004). LCA has been applied for environmental assessment of remediation in a number of studies reported in the literature (Lemming et al. 2010b), but these have mostly focused on off-site remediation and soil pollutants such as hydrocarbons, polycyclic aromatic hydrocarbons (PAHs) and metals. Newer studies, however, included *in situ* remediation of soil and groundwater in their LCA, e.g. for the comparison of a permeable reactive barrier versus a pump-and-treat solution for a groundwater plume (Higgins and Olson 2009) and for the comparison of chlorinated solvent remediation by enhanced bioremediation, thermal conduction heating and off-site treatment respectively (Lemming et al. 2010a)

Chlorinated solvents and petroleum hydrocarbons are frequent groundwater contaminants and a spill may serve as a long-term source to groundwater contamination. However, although relevant for soil remediation, primary impacts due to groundwater contamination have to date only been included in LCA at very few sites (Lemming et al. 2010a). This may be due to the fact that deeper soil layers and groundwater have traditionally been neglected in fate models used for characterization of toxic emissions in LCA.

Currently, there are no legislative or regulatory incentives to incorporate environmental assessments or sustainability assessments into the remediation selection process. Therefore, in reality, cost considerations are often the single most important decision parameter and life cycle impacts are not addressed in most feasibility studies. However, recently an increased focus on holistic decision-making regarding remedy selection for contaminated sites remediation has been observed both in Europe and the US, where forums and networks for *sustainable* or *green* remediation have been established. Examples of such initiatives are Sustainable Remediation Forum U.S. (SURF), Sustainable Remediation Forum UK (SuRF UK) and Green Remediation by US EPA (2008).

EXAMPLES OF LIFE CYCLE ASSESMENT APPLIED TO CONTAMINATED SITE REMEDIATION

Life cycle assessment (LCA) was used for quantification of the environmental impacts associated with a cleanup strategy for two sites in Denmark. LCA is an established and systematic method for assessment of environmental impacts related to a defined function. It includes and compares a wide range of environmental impacts caused by the remediation activities such as global warming potential, acidification potential, photochemical ozone formation, human toxicity potential, ecotoxicity potential, resource use etc. Furthermore, the impact assessment has here been extended to cover local human toxic impacts from the on-site contamination via contaminated groundwater. This assessment therefore gives a more complete and holistic comparison of remedial actions than methods focusing only on global or regional impacts or single indicators such as “carbon footprint”. Site-specific numerical transport models were used to estimate the mass discharge from the contaminant source in the baseline scenario (no remediation) and a number of remediation scenarios. These results were used to predict remedial timeframes to reach a predefined remedial target. Furthermore they provided important inputs as design parameters of the different remediation systems compared and constituted the basis for estimating the local toxic emission to groundwater including formation of degradation products.

The assessment of timeframes and environmental impacts related to remediation was applied to two case studies, which both represents clay till sites contaminated with trichloroethene (TCE). For Site 1, the following remediation techniques were compared: (1a) *in situ* enhanced bioremediation, (1b) *in situ* thermal remediation, and (1c) excavation and *ex situ* treatment. The assessment for Site 2 compared two *in situ* options for remediating the site: (2a) *in situ* enhanced bioremediation, and (2b) *in situ* chemical oxidation.

The results for Site 1 showed that enhanced bioremediation by enhanced reductive dechlorination was an environmentally preferred option compared to *in situ* thermal remediation and excavation with *ex situ* soil treatment. However due to the long timeframe of the bioremediation option, there are significant local toxic emissions to groundwater especially due to vinyl chloride formation. These local toxic impacts were, however, lower than the regional and global toxic impacts generated in the other remediation scenarios (Lemming et al. 2010a). The analysis of Site 2 showed that *in situ* chemical oxidation using potassium permanganate generates higher environmental impacts than the enhanced bioremediation of the trichloroethene-contaminated site (Lemming et al. 2012). The LCA gave insight into the contribution to environmental impacts of the different subparts of each remediation system and can be used to suggest environmental improvements of each system.

FINAL REMARKS

Chlorinated solvents and petroleum hydrocarbons from contaminated sites pose a risk to groundwater resources. It is suggested that a holistic comparison of remedial alternatives and their life cycle impacts should be used more frequently in the future,

so that the investments made in remedial efforts can be better balanced and optimized.

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