Improving the Sustainability of Source Removal

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ABSTRACT: There is a growing recognition of the importance of making hazardous waste remediation more sustainable, and thereby minimizing its economic, environmental and social impacts. The attention of sustainable remediation practitioners has thus far been focused on remediation of lower concentration targets, such as dissolved plumes, where reliance on green techniques that mimic naturally occurring processes such as bioremediation may be particularly effective. There has been less attention, however, on source removal, such as of dense non-aqueous phase liquid (DNAPL) source areas. At sites where achievement of stringent remedial goals is necessary in a short timeframe, aggressive source remediation is required. Among the various methods of “aggressive” (but efficient) source remediation / removal that are currently available, many require excavation, which can be highly energy-intensive (at deep sites or if the distance to off-site treatment or disposal is relatively far) and tends to strongly impact neighborhoods.

In situ technologies such as soil vapor extraction (SVE), multiphase extraction and in situ chemical oxidation are less disruptive than excavation but frequently produce diminishing returns due to diffusion-limited mass transport in the subsurface. Life Cycle Analyses (LCAs) were conducted for four sites in Germany (Hiester et al. 2003; Hiester and Schrenk 2005) where SVE was later followed by In Situ Thermal Remediation (ISTR), and at one site in Denmark (Pfeilschifter et al. 2007), where SVE and ISTR were compared with excavation/off-site treatment, and SVE was again followed by ISTR. Though site specific conditions such as volume, contaminants and depth below subsurface differed widely, each of the LCAs calculated for those site-specific conditions showed that SVE consumed more energy, produced more waste and generated more greenhouse gases than ISTR, while requiring a lengthy or even indefinite period of time to remove sufficient contaminant mass to achieve site closure. Whether or not excavation compares well with ISTR in an LCA depended primarily on the transport distance to a suitable disposal or treatment site. ISTR offers the reduced neighborhood impacts of an in situ remedy combined with the ability to achieve predictable, timely site closure. ISTR has restored impaired properties enabling beneficial reuse, even to residential standards in a number of cases. It also has produced results consistent with restoration of groundwater, an increasingly scarce resource. An effective robust source removal technology such as ISTR that minimizes environmental, economic and social impacts on a life-cycle basis can thus turn out to be the most sustainable source removal solution for such sites, and should be considered during remedy selection.

INTRODUCTION AND METHODOLOGY

In the context of soil remediation, Life Cycle Assessment (LCA) is the use of a decision support system to determine the environmental burdens caused by the remediation itself, including the impacts of resource consumption, energy usage, transportation emissions, and toxicity (Volkwein 2000; SURF 2009). LCA is beginning to be considered as a supplement to the evaluation of standard remedy selection factors such as the nine CERCLA (i.e., Superfund) criteria defined in the U.S. Code of Federal Regulations (40 CFR Part 300). Among those criteria, two are considered *threshold* criteria that every remedy must attain: (a) protection of human health and the environment, typically defined by attainment of cleanup standards; and (b) compliance with applicable or relevant and appropriate requirements (ARARs), which include adherence to a range of federal, state and local laws and regulations. Remedial alternatives are then compared in light of five *balancing* criteria: short- and long-term effectiveness; implementability; reduction in mobility, toxicity, and volume of contaminants; and, cost. In arriving at selection of a preferred alternative, state and community acceptance are also considered as *modifying* criteria. Both federal and state programs have broadly adopted these nine criteria for remedy selection. While sustainability is not explicitly a component of remedy selection under this rubric, it is implicit in a number of the criteria. LCA can in addition be employed to provide a rigorous method of examining the sustainability of remedial options.

We review several examples of the use of LCA at sites where source removal of NAPL was required, which illustrate how LCA can be used as a supplement to the remedy selection process.

RESULTS AND DISCUSSION

Example 1. Four SVE/TESVE Sites in Germany. LCA was used to evaluate the performance of 'cold' (i.e., ambient temperature) Soil Vapor Extraction (SVE) compared to subsequent application of thermally-enhanced SVE (TESVE) at four German sites: Plauen Gasworks, Mühlacker Landfill, and dry cleaners in Albstadt and in N. Germany (Hiester et al. 2003; Hiester and Schrenk 2005). At the first three of the TESVE sites the heat source was injected steam, while at the fourth conductive heating was utilized. TESVE achieved the remedial goals in 3.5, 15, 3.5 and 4 months, respectively, which was on average <9% of the time estimated for 'cold' SVE, based on an optimistic extrapolation of the observed rates of mass removal during 'cold' SVE. In other words, in all likelihood 'cold' SVE would have taken much longer than estimated to achieve the goals, if indeed it could have done so. The LCA indicated that 'cold' SVE consumed twice the energy as TESVE and caused significantly more environmental impacts, in terms of cumulative energy demand, total waste, fossil resources, land use, global warming, acidification and photo-oxidant formation. The extrapolated SVE operation time, estimated using a realistic extraction rate was 10 years, at least ~12 times longer than the actual TESVE operation time (completed after 0.55 yr on average). Less than 7% of the overall TESVE cost was expended on soil heating, and the total cost of TESVE averaged only 40% that of 'cold' SVE (Hiester et al. 2003; Hiester and Schrenk 2005).

Example 2. Reerslev ISTR Site, Denmark. In Reerslev, Denmark a source area (hotspot) containing >2.5 tonnes of chlorinated solvents was present in a low permeability clay layer. The source was situated in a residential area with single-family houses and beneath an existing graveyard adjacent to a church. The contamination caused a serious risk to the local groundwater resource, one of the most important in Denmark, supplying water to 50,000 homes in the Copenhagen metropolitan area.

The low permeability geology and the location of the area adjacent to residences and the graveyard left only a few realistic remediation alternatives. In addition, very strict clean-up criteria were essential to reach the objective of eliminating the groundwater risk. Risk assessment calculations had shown that a large contaminant mass removal itself would not reach the goal of eliminating the risk to the valuable groundwater aquifer. To reach the goal of the remediation, all DNAPL at the site had to be removed and the post-treatment soil concentrations of chlorinated solvents had to be <1 mg/kg in the entire area.

The complex geology of the area consists of 8-10 meters of clayey till underlain by an unsaturated zone of approximately 15 meters of alternating layers of coarse grained glaciofluvial deposits (Figure 1). About 25 meters below ground surface (bgs) a thin and discontinuous clay layer accounts for the bottom of a shallow secondary aquifer. Underneath this is situated a very high yielding primary aquifer in a thick layer of Danien bryozoan chalk.

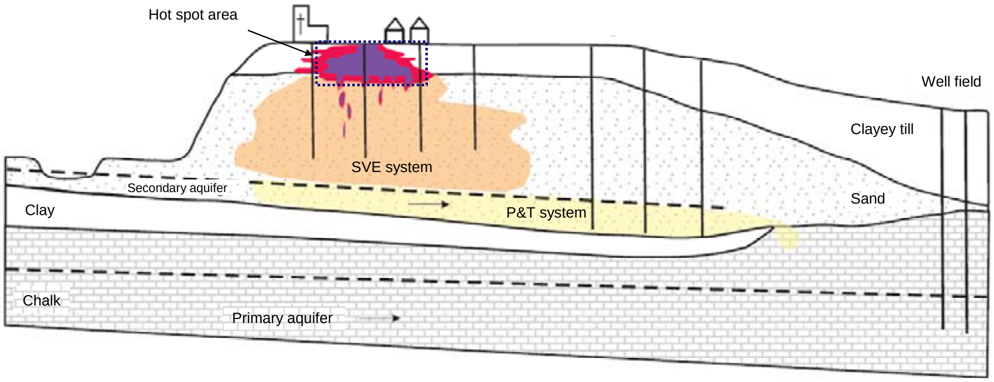


FIGURE 1. Geological cross section showing conceptual site model of the contamination.

Subslab ventilation of the houses was implemented immediately to prevent health risk to the families living in the vicinity. To prevent further spreading from the hotspot area, an SVE system in the unsaturated zone was established simultaneously with a pump-and-treat (P&T) system in the secondary aquifer. Results from several groundwater model simulations, however, clearly showed that due to diffusion limitations, the initial cleanup effort with SVE and P&T for protecting the municipal well field would be a nearly infinite process.

Remedy Selection Process. Three main remedy solutions were considered for protection of the important municipal well field (Table 1). The basis for these choices was that they all should be able, in a reliable and predictable way, to eliminate the risk to the groundwater resource. For the same reason, several in-situ remediation methods were disqualified due to being inefficient for hotspot removal, multiphase extraction (MPE), in situ chemical oxidation (ISCO) and enhanced reductive dechlorination (ERD) (Faurbye and Ploug 2005).

TABLE 1. Potential solutions for remediation at Reerslev.

	In-Situ Thermal Remediation by ISTD
	Excavation and off-site treatment
	Leaving and cutting off hotspot by SVE

In addition to remediation efficiency, the methods were evaluated relative to a wide range of environmental impacts, and an overall impact analysis including cost was made. Selected environmental impacts evaluated are summarized in Table 2. All potential effects were evaluated as having either no, low, moderate or high effect.

TABLE 2. Environmental impacts – evaluation parameters.

	Activities	Impacts		Effects	
Setting-up	Transport Excavation Drilling Building equipment Commissioning	Consumables	Power Fuel/gas Plastic Concrete Iron/steel Activated carbon	Resources	Inadequate raw materials Metals Sand/gravel Water
Operation	Operation period Electrical effect Supervision Service	Emissions	CO_2, CO, NO_x, SO_4 VOCs Noise and vibrations Dust or odor	Environment	Global warming Acidification Toxicity Landfill Dangerous waste
Dismantling	Transport Waste	Exposure	Risk of fire or explosions Dangerous work Inconvenience/disturbance of neighbors	Human	Working environment Inconvenience/disturbance of neighbors

In relation to the overall quantitative impact analysis, a number of concerns were also evaluated and taken into account, e.g., the risk of leaving residual contamination, impacts on the surroundings, resettlement of residents, moving/closing down gravesites and disturbing churchgoers.

Role of LCA. Later during the remedy selection process, an impartial LCA study was made by a group of students from the Technical University of Denmark (Pfeilschifter et al. 2007). The LCA study was based on the same three technologies as in the preliminary evaluation: electrically-powered conductive heating, excavation and off-site treatment, and SVE in the unsaturated sand zone below the clayey till hotspot.

Six scenarios were evaluated: best case (BC)/worst case (WC) excavation, SVE for 30 years/100 years, and conductive heating for 1 year and 0.7 year. For each scenario the potential impacts of emissions, toxicity, waste and resource consumption were weighted. In order to investigate the origin of the environmental impacts in greater detail, each technology was subdivided into its major subsidiary processes (e.g., transport/treatment of soil, demolition of houses, electricity production, production of steel).

To facilitate a comparison of the technologies of concern, the three scenarios considered more likely were identified (Table 3).

TABLE 3. More probable scenarios according to the LCA.

Scenario 1-3	**Reasoning**
Heating in 1 year	More conservative estimate
Excavation – worst case (WC)	Believed to be more accurate
Cutting-off hotspot by SVE in 100 years	Based on extrapolation of mass removal rate of existing SVE system, 30-yr SVE assumed to be unrealistic

Analysis and Results. In general, the preliminary evaluation (Faurbye and Ploug 2005) proved to be very consistent with the LCA. Figure 2 shows that in particular, impacts of the Excavation 2 (WC) scenario and the 100-year SVE solution were judged to be greater than the impacts of other technologies relative to use of resources, waste and toxicity. Moreover, when the qualitatively described impacts (working environment, inconvenience and remediation efficiency) were also considered, the long-term SVE solution proved to be the technology with the highest environmental impact (Figure 3).

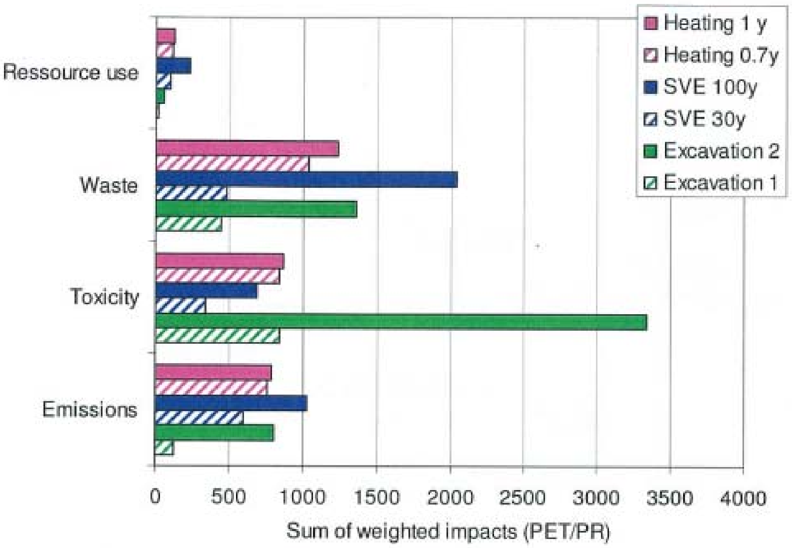


FIGURE 2. Sum of weighted impacts in terms of resource consumption, normalized as per capita reserves (PR); and waste, toxicity and emissions, normalized as targeted per capita equivalents (PET) (Pfeilschifter et al. 2007). Excavation 1 = BC; Excavation 2 = WC scenario.

As mentioned in the earlier section, three of the six scenarios were considered to be more probable (marked with boxes in Figure 3). The WC excavation scenario was prominent as a consequence of both toxicity and inconvenience, which means that the disturbance of neighbors and churchgoers was weighted as an important impact – due to the site's location in the middle of a residential area, requiring demolition of two homes.

Heating for either duration was associated with somewhat greater resource consumption than excavation. This was largely due to the relatively close proximity of the treatment facility from the site (80 km). We estimate that if the soil had to be transported more than approximately three times that far (240 km) to a treatment facility or landfill, the overall resource consumption for heating and excavation would have become equivalent. Since many such locations are at least that far, the resource consumption for excavation may often exceed that of ISTR.

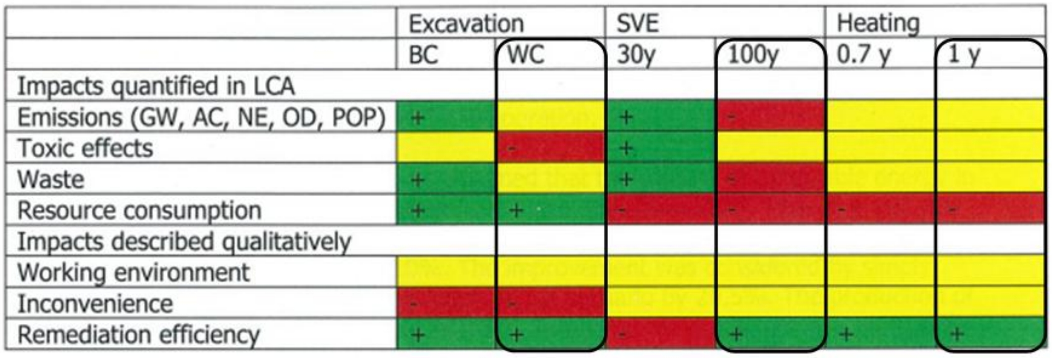
According to the LCA, a long-term SVE solution would produce the heaviest impact, while excavation and heating would yield lesser but different kinds of impacts.

One parameter that was not considered in the LCA was the risk of leaving residual contamination. Since excavation in this sensitive area in all probability would require the use of sheet piles, the considerable risk of not removing the problem despite a really extensive effort had to be taken into account. This particular uncertainty together with the total sum of impacts (emission, consumables, etc.) meant that with regard to the overall evaluation, excavation was believed to be environmentally the most undesirable option for removal of the hotspot.

ISTD Implementation. At Reerslev, the selected technology was thermal remediation by In Situ Thermal Desorption (ISTD), which is the simultaneous application of conductive heating and vapor extraction. A soil volume of 11,100 m^3 was treated with 147 heater wells. The heating period was 169 days.

The preliminary evaluation and the LCA had both been based on a soil volume of 12,560 m^3. The corresponding energy usage for ISTD had been estimated to be 6.7 MWh and 4.7 MWh for 1 and 0.7 years of treatment, respectively (Pfeilschifter et al. 2007) with 100 heater wells. Converted to the actual soil volume of 11,100 m^3, this corresponds to a predicted 5.9 MWh and 4.1 MWh for 1 and 0.7 years, respectively.

The actual energy consumption during the ISTD project was 3.99 MWh, corresponding to 342 kWh/m^3. The real energy consumption was thus rather close to the LCA estimate of 0.7 yr and a good deal less that the “most probable” scenario of 1 yr.



	Excavation		SVE		Heating	
	BC	WC	30y	100y	0.7 y	1 y
Impacts quantified in LCA						
Emissions (GW, AC, NE, OD, POP)	🟩 +	🟨	🟩 +	🟥 -	🟨	🟨
Toxic effects	🟨	🟥 -	🟩 +	🟨	🟨	🟨
Waste	🟩 +	🟨	🟩 +	🟥 -	🟨	🟨
Resource consumption	🟩 +	🟩 +	🟥 -	🟥 -	🟥 -	🟥 -
Impacts described qualitatively						
Working environment	🟨	🟨	🟨	🟨	🟨	🟨
Inconvenience	🟥 -	🟥 -	🟨	🟨	🟨	🟨
Remediation efficiency	🟩 +	🟩 +	🟥 -	🟩 +	🟩 +	🟩 +

FIGURE 3. Comparison of remedies. Green/+ indicates best environmental performance, red/- indicates worst performance and yellow/no sign indicates intermediate environmental performance (Pfeilschifter et al. 2007). “Most probable” scenarios are marked.

A comparison of pre- versus post-treatment tetrachloroethene (PCE) soil concentrations (Figure 4) shows >99.99% removal, with all remediation goals being met at the ISTD project in Reerslev. No health or safety issues emerged and all authorities and residents in the community were satisfied with the result of the remediation.

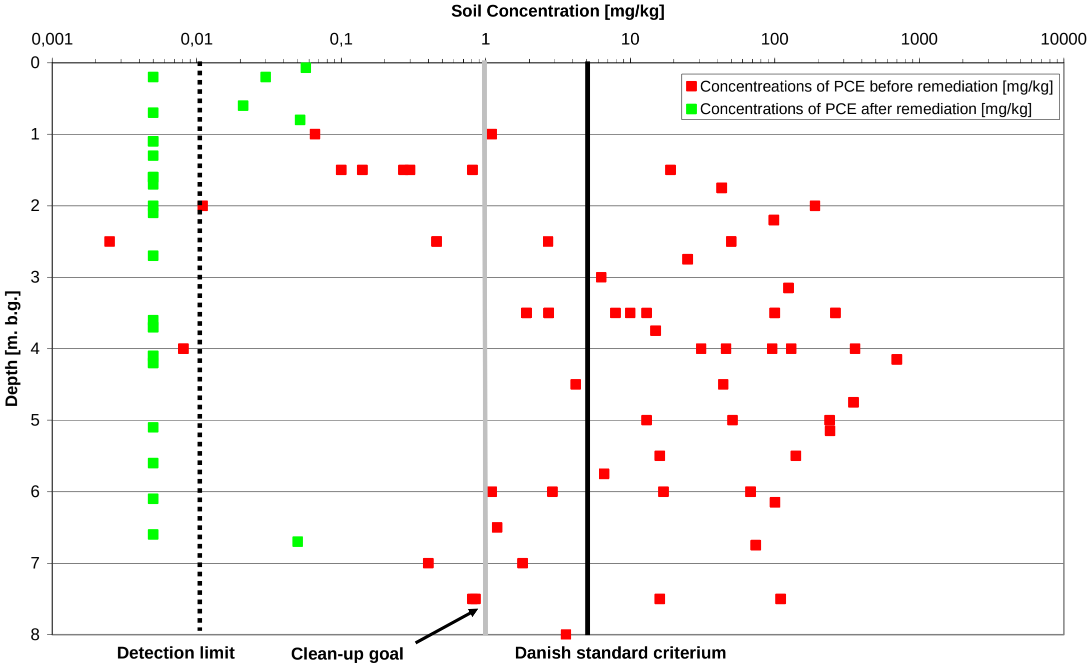


FIGURE 4. Concentration of PCE in Reerslev soil samples before and after ISTD treatment (data from Nielsen 2010).

Economics. In the original preliminary analysis (Faurbye and Ploug 2005) the relative cost of each technology had been evaluated in millions of Euros (Figure 5).

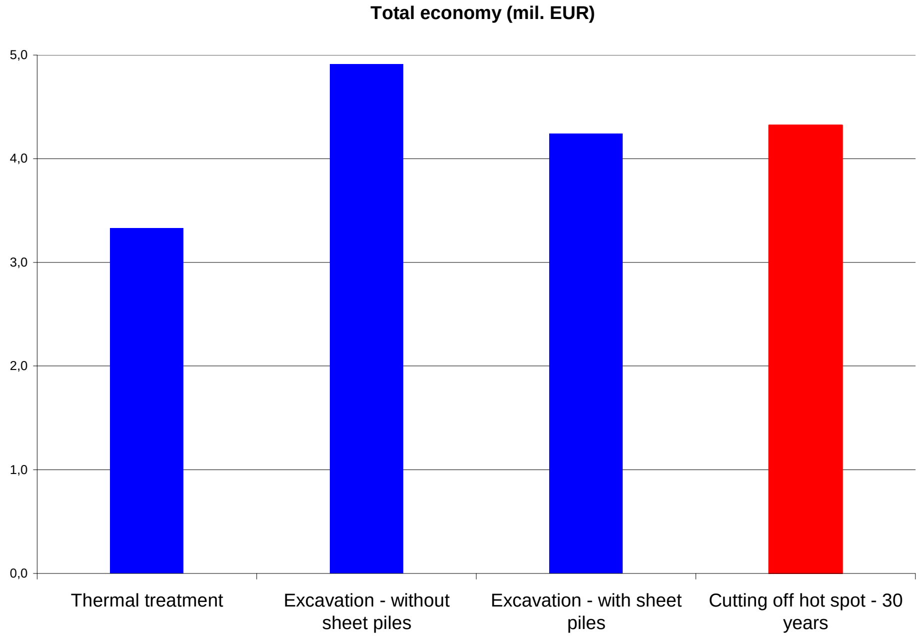


FIGURE 5. Estimated total cost (mil. €) of evaluated technologies.

For remediation of 12,560 m^3 soil, ISTD, with a total cost of €3.3 million was estimated to be the most cost-efficient alternative. The final ISTD project cost turned out to be about €2.9 million, and thus both the remediation result and the cost of the project proved to be predictable and reliable.

CONCLUSIONS

LCAs conducted at five sites where ISTR was compared with SVE and excavation / off-site treatment concluded that ISTR had lower overall environmental impacts and costs. In each instance, the completed ISTR project results were consistent with results predicted by the LCA.

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