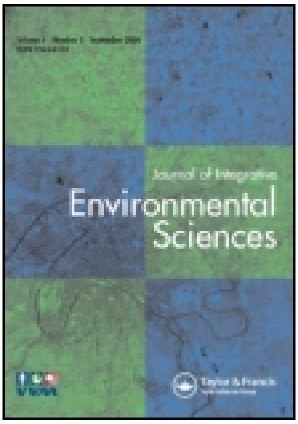

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Can thermal soil remediation be sustainable? A case study of the environmental merit of the remediation of a site contaminated by a light non-aqueous phase liquid (LNAPL)

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Can thermal soil remediation be sustainable? A case study of the environmental merit of the remediation of a site contaminated by a light non-aqueous phase liquid (LNAPL)

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When evaluating remediation technologies for contaminated soil and groundwater, the beneficial effects of the remediation, namely cleaner soil and groundwater, are mostly emphasized without consideration of the environmental impact of the remediation activities themselves. In the present study, the environmental impact of two soil remediation techniques was evaluated. Based on the detailed analysis of a case study, the results of a life cycle–based analysis (Risk Reduction, Environmental Merit and Costs (REC)) were compared with the results of a best available technology not entailing excessive costs (BATNEEC) analysis, a method that is currently applied in Flanders (Belgium) to evaluate the feasibility of remediation technologies for soil and groundwater. According to the REC analysis, in situ thermal treatment showed a lower global environmental impact than soil excavation and off-site treatment, mainly because there were fewer emissions from the transport of contaminated soil. Within the environmental aspects group of the BATNEEC method, soil excavation performed better than thermal soil remediation because it obtained a better score to meet the legal objectives for soil and groundwater quality. It also showed fewer environmental liabilities and obtained a better score for a decrease in the contaminants' content in soil and groundwater. The BATNEEC method does not take into account the emissions from the transport of the soil. Despite these differences between both methods, thermal remediation technology obtains the best overall score in terms of both assessment methods (taking into account the environmental, financial, and technical aspects). Although an life cycle analysis (LCA) based evaluation method is much more complex and requires much more data than a classical BATNEEC analysis, both evaluation tools could be used in a complementary way. A preliminary selection of remediation technologies could be based on a BATNEEC analysis, followed by a detailed analysis of the selected remediation options by means of LCA.

Keywords: BATNEEC; energy consumption; environmental merit; LCA; remediation

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Abbreviations: LCA, life cycle analysis; REC, Risk Reduction, Environmental Merit and Costs; BATNEEC, best available technology not entailing excessive cost; LNAPL, light non-aqueous phase liquid

Introduction

Selection of remediation techniques for contaminated land

The decision process for selecting the technique for remediation of contaminated sites traditionally focused on the clean-up level, the time required for the remediation, the economic resources, and the best available technologies. Other factors that are relevant for the remediation of contaminated sites include the sustainability of the remediation process and the view of the stakeholders on the remediation solution (Vik et al. 2001). Sustainability of the remediation of contaminated land takes into account three main aspects: (1) economic aspects (e.g. cost of remediation), (2) ecological aspects (e.g. environmental aspects of remediation, such as emissions to surface waters), and (3) social aspects (e.g. communication to stakeholders). In some countries, the selection of soil remediation options is based on the best available technology (BAT). Some other countries, including Flanders, take the best available technology not exceeding excessive cost (BATNEEC) as a criterion for selecting soil remediation options. Despite the fact that BAT is likely to represent the most technologically feasible tool for soil remediation, BATNEEC seems a more suitable framework for decisions regarding soil remediation projects.

Although soil remediation is often considered to be a completely positive process because of the reduction or removal of soil contamination, the overall consequences and impacts of the soil remediation process should be considered. Under the European Commission's Framework Programme 5, the Concerted Action The Contaminated Land Rehabilitation Network for Environmental Technologies in Europe (CLARINET) brought experts and regulators from 16 European countries together to identify the means by which contaminated land could be managed in an effective but sustainable manner. As a follow-up action to implement the recommendations of this Concerted Action, the Sustainable maNagement of sOil and groundWater under the pressure of soil pollution and soil contaMinAtioN (SNOWMAN) project is to analyze the possibilities for improving the co-operation between national research programs, in Europe, in the field of soil and groundwater management where there is the presence of contamination (Vermeulen et al. 2006). This leaves us with the fundamental question: what constitutes sustainable remediation of contaminated soil?

Harbottle et al. (2006) defined five criteria that have to be met in order to classify a remediation project as "sustainable" (Table 1).

In the present study, more attention will be paid mainly to the environmental impacts of the remediation process (criteria two and three), while only limited attention will be paid to economic and social aspects.

Environmental impacts of soil remediation

The environmental impacts of soil remediation are one of the aspects that deserve more attention during soil remediation. Since the 1990s, several tools have been developed to assess the environmental impacts of processes and products, such as eco-indicators and other tools based on life cycle analysis (LCA). Since the last

Table 1. Five criteria for a sustainable remediation project (Harbottle et al. 2006).

Criterion	Comment
Future benefits outweigh cost of remediation	Besides the economic cost, societal benefits also have to be taken into account (e.g. van Wezel et al. 2007)
Overall environmental impact of the remediation process is less than leaving the land untreated	Boundaries of the impact assessment have to be defined: which impacts do you take into account and which not?
Environmental impacts due to the application of the remediation process are minimal and measurable	Boundaries of the impact assessment have to be defined. There should be a consensus on the way to express ‘‘environmental impacts’’ in an objective way
The timescale over which the environmental consequences occur (including intergenerational risk) is part of the decision-making process	The soil should be restored in a sustainable manner so that both current and future generations can satisfy their ecological, economic, and social needs
The decision-making process includes an appropriate level of engagement of all stakeholders	What can the role of different stakeholders be in every aspect of the decision-making process?

decade, LCA has been gaining wider acceptance as a tool for the quantification of environmental impacts and evaluation of improvement options throughout the life cycle of a process, product, or activity (Tukker 2000). An LCA is carried out in four distinct phases: (1) definition of goal and scope, (2) life cycle inventory, (3) life cycle impact assessment, and (4) interpretation (Hendrickson et al. 2006). Historically, LCA has mainly been applied to products, but several examples (e.g. Klemeš et al. 2007) show that it can assist in identifying more sustainable options in process selection, design, and optimization.

A life cycle framework, including a life cycle management approach structuring environmental activities and LCA for a quantitative examination, can be helpful for the selection of site remediation options with minimum impact on the ecosystem and human health (Diamond et al. 1999). During the last 10 years, several instances have emerged in which a life cycle approach has been applied to the remediation of contaminated sites.

In a literature review, Suer et al. (2004) illustrates that the result of LCA is highly dependent on the method used and that the choice of impact categories heavily affects the outcome of an LCA study. Moreover, the collection of additional data concerning temporal and spatial effects should be integrated into the evaluation of contaminated sites (Suer et al. 2004).

Besides primary impacts, associated with the state of the site, and secondary impacts, associated with the site remediation itself (Toffoletto et al. 2005), LCA for contaminated site management should also account for tertiary impacts, associated with the effects of the reoccupation of the site (Lesage et al. 2007b). Therefore, different scenarios could be considered. For example, Cadotte et al. (2007) considered two different remediation scenarios: one based on a fast treatment time and another on a low environmental impact. The relative sustainability of a soil remediation project also depends on the objectives of the remediation (Harbottle et al. 2008a); hence, it is not possible to give an overall ‘‘sustainability score’’ to a specific soil remediation technique.

Policy on soil remediation

Approximately 250,000 sites in Europe require clean-up, while the European Environmental Agency estimates that nearly three million sites are potentially polluted (EEA 2007). In Flanders, which covers a small, but densely populated area (13522 km^2, with six million inhabitants) in Europe, the number of potentially polluted sites is estimated to be approximately 76,200, whereas almost 20,000 of these sites have been subjected to a soil investigation procedure (OVAM 2008).

In 1995, Flanders adopted its Soil Remediation Decree. This decree contains an obligation to carry out an investigation of every transfer of land in which a "risk activity" is or has been developed. A distinction between "historical contamination" (before 28 October 1995) and "new contamination" (after 28 October 1995) is also made. Soil clean-up standards follow a risk-based approach and are used to indicate a level of contamination that if exceeded could cause significant harm to human health (Dries et al. 2008).

On 27 October 2006, the Flemish Parliament adopted a new decree that entered into force in 2008 and that was slightly modified by the decree of 12 December 2008 (Dries et al. 2008). The new decree is simpler and allows a more efficient, risk-based management of soil remediation and soil transfer (Van Keer et al. 2009). The purpose of the decree is to avoid the land that is at risk of being transferred to a buyer who is not aware of the possible contamination of the land in question (OVAM 2006).

Sorvari et al. (2009) point to the fact that existing policy instruments do not promote sufficiently eco-efficient site remediation technologies. Besides the development of a more eco-efficient policy for contaminated site management, there is a need to promote the use of more eco-efficient site remediation techniques. An important aspect of this is the development of methods that allow assessment of the eco-efficiency of site remediation options. In addition, the knowledge of decision support tools that take into account eco-efficient or even sustainable remediation options, among stakeholders that have to decide on which site remediation options to pursue, should be improved.

Aim of the present study

In the present study, two tools that can be used to select soil remediation alternatives were compared. Although some of the tools also take into account financial, technological, and social aspects of soil remediation, the focus here will be upon the environmental impacts of the site remediation project. As such, this study will not provide a quantitative analysis of all aspects of "sustainable soil remediation" as only the environmental merit and the costs will be quantified, whereas other aspects will only be addressed briefly in a qualitative way. This comparison between two tools that are used to assess the environmental impacts of soil remediation technologies is presented in the form of a case study based on a remediation project in Flanders (Belgium), where an in situ soil remediation technique is compared with an ex situ soil remediation technique. Several studies point to the fact that soil excavation followed by transportation has a more important environmental impact than in situ techniques (e.g. Diamond et al. 1999; Page et al. 1999; Blanc et al. 2004). Although transportation is often a restraining factor where the sustainability of ex situ soil remediation is concerned, it was considered in the present case study because of the limited distance of soil remediation centers compared to other case studies where contaminated soil had to be transported over a distance of more than 300 km (e.g. 500 km in Blanc et al.'s study (2004); up to 332 km in Harbottle et al.'s study (2008b)). Moreover, excavation combined with disposal or off-site treatment is the most common soil remediation strategy applied in Flanders. Flanders has 20 permitted soil remediation centers, specializing in the treatment of soil coming from soil remediation projects. These soil remediation centers are mostly situated outside built-up areas or in an industrial zone.

The environmental merit of the site remediation projects was evaluated by using the available software: BATNEEC, which is commonly used in Flanders to select adequate soil remediation techniques, and Risk Reduction, Environmental Merit and Costs (REC) (Beinat et al. 1997), an LCA-based software package. The choice of the software was based on a screening of commonly used tools and software packages for the evaluation of soil remediation. Finally, the remaining methods where methods that were available at the moment of the study, and for which the necessary input data could be obtained.

Methodology

Description of the case study

The case concerns a former industrial site where a distribution center for new and second-hand cars has been operating since 1970. The depth of the groundwater table is between 2.5 and 3 m. For the removal of a protective wax layer from new cars, several solvents have been used since 1970; initially, a mixture of 1.5% of petroleum in water was used, but in 1988, petroleum was replaced by Finalan, a solvent consisting of aliphatic hydrocarbons. In 1990, Finalan was replaced by another solvent, namely Exxsol, which was easier to recycle after use. During the removal of the wax layer from the cars, a suspension of Exxsol in water is sprinkled on the cars. The emulsion that is released after washing the cars is collected in a gut. Because of a leakage in the gut, soil and groundwater have been contaminated with Exxsol. Since Exxsol is characterized by a density of less than 1 g/cm^3 (Table 2), it forms an light non-aqueous phase liquid (LNAPL) layer on the groundwater, at a depth of 2.5–3 m below the ground surface. The LNAPL contamination occurs in unconsolidated deposits consisting of landfills and loess. Loess consists of wind-blown silt and clay and is the predominant soil lithology in the area.

Exxsol is an aliphatic hydrocarbon with 13 C-atoms. It is characterized by a boiling point between 200°C and 240°C, by low volatility, and by limited solubility in

Table 2. Physical properties of Exxsol and mineral oil.

	Exxsol	Mineral oil
Pour point (°C)	−36	–
Boiling point (°C)	200°C–240	170°C–139
Autoignition temperature	200°C	220°C
Flash point	88°C	55°C
Flammable limits (vol%)	0.6–0.7	0.6–5
Solubility in water	0.10 w%	Neglectable
Density at 15°C (g/cm^3)	0.796	0.820

water (Table 2). Its physical properties are similar to the properties of mineral oil (Table 2). No target values for soils contaminated with Exxsol are given in Flemish environmental legislation, since it is a relatively unknown contaminant. Because of its similarity to mineral oil, soil remediation values for mineral oil will be taken as threshold values that have to be reached after remediation. The remediation values for mineral oil in soil and groundwater in Flanders are, respectively, 1500 mg/kg and 500 μg/l.

Possible remediation technologies

For more volatile contaminants, technologies such as air sparging or vapor extraction are only effective in highly homogenous materials, so it is difficult to remove large masses of LNAPL (Huntley and Becket 2002). Other commonly used remediation technologies for soil and groundwater with LNAPL contamination consist of pump-and-treat processes (e.g. Voudrias et al. 1994), multiphase extraction, surfactant enhanced recovery (Mulligan et al. 2001), and bioremediation (Langwaldt and Puhakka 2000). For the present case, the environmental impacts of a thermal remediation technique will be compared with the environmental impacts of excavation and off-site cleaning of the contaminated soil. Both techniques will be discussed in more detail in the following sections. A pilot test with a thermal soil remediation facility was performed on the site, from which the necessary input data for the LCA model could be obtained. The other remediation alternative (soil excavation) was investigated because in Flanders, 40% of soil remediation projects still rely on soil excavation and off-site cleaning.

Thermal soil remediation

The thermal remediation technology applied here is based on thermal conduction, which can be used to remove organic pollutants from the soil leaving very low levels of pollution behind. Therefore, a network of heating pipes (made of stainless steel) is placed into the soil. The heating elements consist of two coaxial steel tubes, of which the outer tube is perforated. During the remediation process, gases at high temperature (700°C–800°C), coming from the combustion chamber, circulate within the heating elements, resulting in the heating of the soil and in the evaporation of volatile pollutants (boiling point $<550^{\circ}$C) contained in the soil (Saadaoui et al. 2008b).

The desorbed pollutants migrate into the heating elements (by diffusion and convection) through perforations in the outer tubes, thanks to negative pressure generated by the Venturi effect. Once inside the heating elements, the desorbed gases (steam and contaminants) are conveyed into the combustion chamber, where they serve as fuels. The chamber is equipped with a purge system in order to maintain the stoichiometry in the system, as the combustion chamber is also equipped with an auxiliary burner (Saadaoui et al. 2008a).

> “The soil itself is heated through conduction. This mechanism is quite unusual in soil treatment technologies, as most heating mechanisms are based upon convection (physically moving a heat-transporting fluid into the contaminated mass). The main advantage of conduction is that it mainly depends on soil moisture and soil mineralogy. As a consequence of this mechanism (conduction), the timing for reaching set temperatures is quite predictable and the cleanliness of the treated material is

> guaranteed as well, since it responds to the same physical laws (temperature, pressure and residence time)" (Deepgreen 2009).

This technology uses less energy than traditional thermal techniques, such as steam injection and electrical heating. Both technologies need a lot of energy for the heating of water and the production of electricity. The thermal remediation technology uses five to 10 times less energy than traditional thermal systems because gases circulate within a closed system, resulting in the maximum re-use of gases and the minimum level of emission of gases. In addition, the contaminants that are desorbed from the soil are captured by the gas stream and used as fuel in the thermal oxidator, which is used to produce gases at high temperatures.

Besides the lower demand for energy, this technology results in lower emissions of CO_2, NOx, and SO_2. Noise pollution is also minimal because no mechanical equipment is used to treat the soil (Saadaoui et al. 2008a).

Soil excavation

The contaminated site is characterized by good accessibility and a hot-spot contamination, which makes soil excavation a feasible remediation option. However, the contamination does not represent an acute risk for the environment, since it is moving very slowly through the soil.

If excavation is selected as a remediation technology, part of the building where the wax layer is removed from cars has to be broken down and rebuilt afterwards. Because this building is not intensively used anymore, this will only have a small impact on other activities of the company.

During excavation, volatile emissions, odor nuisance, and noise from excavators and transport equipments are possible adverse environmental effects. In addition, fuel is used to operate the diesel engines of the excavators, which is estimated to be approximately 0.1 l of diesel per m^3 of excavated soil. If the contaminated soil is (periodically) stored on the site itself, precautions have to be taken to avoid secondary contamination of the soil and groundwater by leaching of the contamination from the excavated soil. If the soil is transported to a soil remediation facility (off-site), the transport of the contaminated soil also has to be taken into account, as well as the treatment of the contaminated soil (e.g. use of chemicals, nutrients to stimulate biological degradation, and others).

Data used as input for the LCA

The collection of data as input used in the REC model was carried out in collaboration with the project engineer, in charge of the soil remediation project. Data could be retrieved from a pilot test that was carried out on the site over a period of 4 weeks. In order to obtain a better overview of the necessary input and to establish the boundaries of the study, a process tree was constructed for both remediation technologies (Figures 1 and 2). Processes that were accounted for in the LCA are indicated in bold. For soil excavation, the fuel consumption of the pumps used to lower the groundwater table was considered, as well as the fuel necessary to operate the excavators and the fuel necessary for the trucks that transport the soil on site and from the site to the remediation facility. In the soil remediation facility, soil will be treated by bioremediation. Therefore, the use of nutrients and energy to

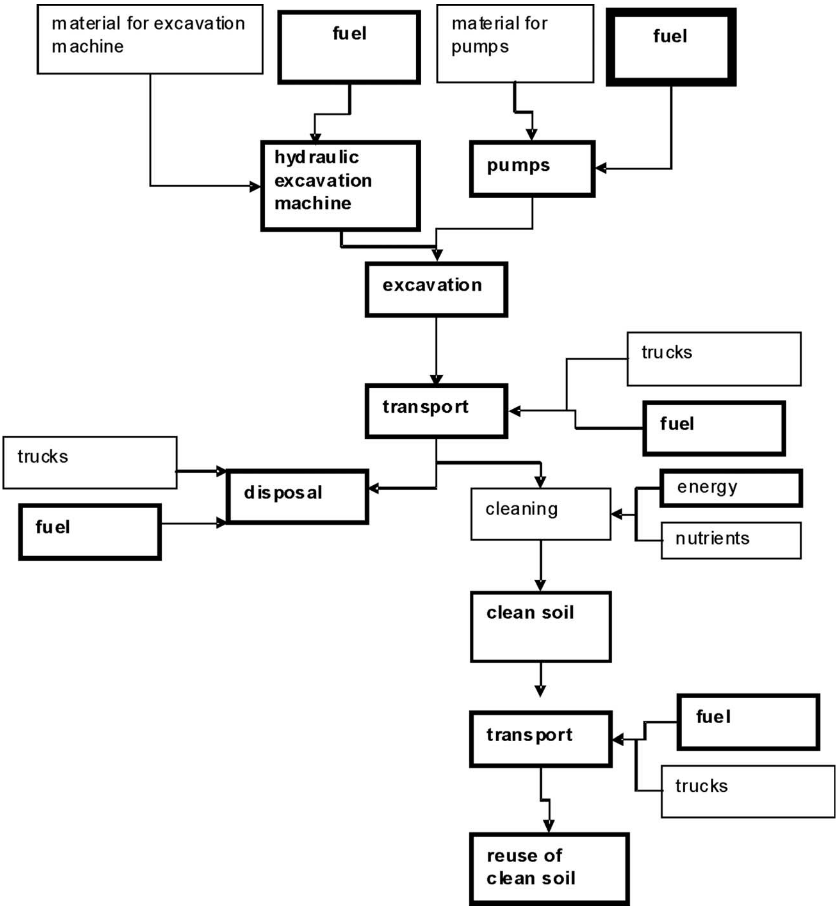

Figure 1. Process tree of soil excavation and off-site treatment.
Note: Processes that were accounted for in the LCA analysis are indicated in bold. The fuel consumption of the pumps used to lower the groundwater table was considered, as well as the fuel necessary to operate the excavators and the fuel necessary for the trucks that transport the soil on site and from the site to the remediation facility. The use of nutrients and energy to carry out the bioremediation was also accounted for.

carry out the bioremediation was also accounted for. Data concerning the cost of the bioremediation were obtained from a soil remediation company.

For remediation with thermal remediation technology, the following processes were considered: the fuel consumption by the groundwater pumps and the consumption of gases by the remediation installation. The company that developed the thermal remediation technology provided financial information concerning the in situ thermal remediation.

The total amount of soil and groundwater that has to be extracted, cleaned, or both, and the target values for contaminants in soil and groundwater that have to be reached were also necessary constituents of the input used in the REC model.

The production of the equipments necessary to perform the remediation (excavators, pumps, trucks, etc.), and the transport of equipment and workers towards and from the site were not included in the analysis.

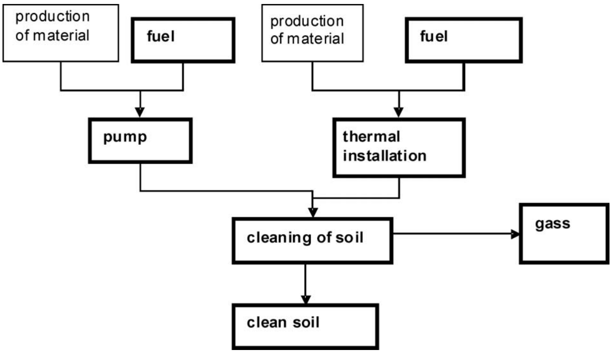

Figure 2. Process tree of soil remediation with thermal remediation technology.
Note: Processes that were accounted for in the LCA analysis are indicated in bold. Following processes were considered: the fuel consumption by the groundwater pumps and the consumption of gases by the remediation installation.

Software used for the analysis

The software packages used for the evaluation of the environmental impacts of the soil remediation process were selected on the basis of some practical criteria:

- Both packages are Excel-based, and do not require specialized computer software.
- They were available free of charge.
- They are relatively easy to use.
- One of the tools (namely BATNEEC) is routinely used in Flanders for the selection of remediation alternatives.

Several other software packages are available for the evaluation of soil remediation techniques and have been used in previous studies for the comparison or evaluation of soil remediation technologies. For example, Volkwein et al. (1999) developed an LCA-based software tool that allows comparison of different remediation options leading to the same level of risk after remediation. Other tools, such as tool for reduction and assessment of chemical and other environmental impacts (Bare et al. 2003), consist of a general impact assessment methodology, developed by the US Environmental Protection Agency, that facilitates the characterization of environmental stressors that have potential effects, including ozone depletion, global warming, acidification, eutrophication, tropospheric ozone (smog) formation, ecotoxicity, human health criteria related effects, human health cancer effects, human health non-cancer effects, and fossil fuel depletion. This method has been applied by Cadotte et al. (2007) to select a remediation option for a diesel-contaminated soil.

It is not the purpose of this article to give an overview of different tools available for evaluating soil remediation technologies. It is, however, important to know that all the tools differ in terms of the impact categories that are taken into account. A critical review of the use of LCA as a tool for evaluating the environmental impacts of soil remediation technologies in 12 studies published between 1997 and 2007 can be found in the study by Lemming et al. (2010).

Risk Reduction, Environmental Merit and Costs (REC)

The REC software (Beinat et al. 1997) consists of a decision support system for the analysis and evaluation of possible clean-up strategies for a contaminated site. The choice of the most effective and efficient strategy for soil remediation of a site is based on three aspects:

- Risk reduction: Risk reduction combines several risk assessment tools for indicating the reduction of risks for humans, ecosystems, and other targets on the site by using remedial actions. The perspective of risk reduction is local.
- Environmental merit: Environmental merit uses life cycle thinking to apply an environmentally balanced approach to remedial actions.
- Costs: Costs are estimated for the full-time span of the operation and expressed on a yearly basis.

The present article will concentrate on environmental merit. Risk reduction is not considered in the present study because the boundaries are defined in such a way that contaminant concentrations have to be below legal threshold values at the end of the remediation, which means that there is no risk associated with the contamination anymore.

Environmental merit includes not only the positive environmental outcomes of the remediation (clean soil and clean groundwater) but also the fact that this is usually obtained at some environmental costs (e.g. the use of scarce resources or secondary pollution of the environment) (Beinat et al. 1997).

Besides primary effects (e.g. electricity consumption by pumps), secondary effects (such as CO_2 emissions by power stations and electricity consumption by the pumps of wastewater treatment plants) are also included. Tertiary effects (e.g. energy required for the construction or repair of pumps present at the site) are not considered because the expected effects would be relatively limited (Beinat et al. 1997).

Best available technology not entailing excessive costs (BATNEEC)

This tool is used in Flanders for the selection of soil remediation technologies. Consideration is given to the best available technical solutions that already have been successfully tested out in practice, and whose cost is not unreasonable in proportion to the achievable result in terms of protecting people and the environment (Pearce and Brisson 1993).

The BATNEEC tool uses a multicriteria analysis taking into account the following aspects:

- Environmental aspects
- Technical aspects
- Financial aspects.

The outcome of this BATNEEC analysis is a selection of three soil remediation alternatives, which provide the following information for each option:

- Estimation of cost
- Expected results

- Expected environmental impacts (risk for surface and groundwater contamination)
- Restrictions for land use.

Results and discussion

LCA according to the REC model

As aforementioned, an LCA consists of four main phases. The goal and scope of the LCA have been addressed in the introduction. In the present section, attention will be paid to the data inventory, the impact assessment, and the interpretation of the results.

LCA was performed by using the REC software. Two alternative remediation options, namely thermal remediation and excavation, were compared with each other. In the inventory step, soil quality, groundwater quality, the use of energy, emissions, the production of waste, and the use of space were analyzed.

Data inventory

Soil and groundwater quality and loss of soil and groundwater. For the evaluation of soil and groundwater quality, the time necessary to obtain a required soil quality is an important consideration. ‘‘Excavation’’ obtains a better score in this respect since it takes less time than an in situ soil remediation technique such as the in situ thermal remediation. In the case of soil excavation, soil will be excavated and transported to a nearby soil remediation facility. The soil will be remediated by stimulated microbial degradation of Exxsol, allowing a reduction of the contamination by 97%, resulting in a final Exxsol concentration of about 19 mg/kg. The excavated soil will be replaced by clean soil that has to be transported to the site. In total, 13,940 tons of soil has to be excavated and replaced, which could take 3 months. Part of a building has to be broken down, but this will not hamper the activities of the company. For the groundwater, the pump-and-treat method is used to manage dissolved plumes emanating from the NAPL source and to remove the NAPL mass from the subsurface, together with the LNAPL phase that forms a smear zone. In the case of soil excavation, 21,600 l of water is withdrawn and cleaned by means of oil *or* water separator and coalescence filters. The extracted groundwater is purified by a series of vessels containing high-density polyethylene filters. Additional purification with granulated active coal is also possible. Because of the relatively low groundwater flow, part of the groundwater (approximately 15,000 l) can be cleaned in a water remediation facility located within the company, whereas the remaining 6,600 l is filtered over membrane filters and discharged into the sewage system.

With thermal remediation, Exxsol concentrations in soil can only be reduced to a value of approximately 200 mg/kg, which is a worse result when compared to excavation and off-site cleaning. However, no soil has to be excavated, transported, and replaced by clean soil.

Loss of soil and groundwater.13,940 m^3 of contaminated soil has to be excavated in the case of ‘‘soil excavation and off-site cleaning’’. Since the soil can theoretically be reused on the site after cleaning, the loss of soil is considered to be zero. With the thermal remediation option, 70 m^3 of contaminated soil is excavated in order to be able to insert steel tubes into the soil. This soil is highly contaminated because the steel tubes are introduced in the most contaminated part of the soil. This soil is not mixed with soil with a low degree of contamination (which happens with soil excavation as a remediation technique for the complete site) and is considered as waste. This contributes to a small loss of soil.

*Generation of waste.*During the soil excavation process, waste is generated by the extraction and purification of groundwater. The waste consists of (almost) pure Exssol (with a total volume of 10 m^3), which was collected during extraction of the LNAPL layer above the groundwater and approximately 10 m^3 of active coal, used for the purification of the groundwater. Applying the thermal remediation technology, as explained above, 70 m^{3}of waste is generated by the insertion of steel tubes into the soil. In a similar way to the remediation by soil excavation and cleaning, 10 m^3 of active coal is used for the purification of the groundwater and has to be discarded after use.

Emissions and use of energy. Despite the fact that the distance to the most nearby soil treatment facility is only 32 km, the transport of contaminated and cleaned soil results in the most important emissions in the case of soil excavation and cleaning because of the consumption of fuel. In addition, the excavation equipment*s* used on site use 0.1 l of diesel per m^3 of soil. During bioremediation of the soil, a significant amount of energy (approximately 7.5 kWh per m^3 of soil) is used for ploughing the soil and for optimization of the environmental conditions to stimulate biological degradation of the contamination.

Space used. In the case of soil excavation, 3000 m^2 is occupied by excavators, trucks, the groundwater remediation installation and others during a period of 1 year. This causes a limited disturbance to the activities of the company, since it only takes a small part of the very large parking lot for new cars. For remediation with the thermal remediation technology, only 1250 m^2 of space is needed, also for a period of 1 year. The difference between both remediation options is explained by the fact that no trucks and excavators are needed on the site during thermal remediation.

The aspects that are included in environmental merit are based on the indications of an LCA carried out for soil remediation and on interviews with soil experts (Beinat et al. 1997).

Based on the effect table (Table 3), both remediation technologies can be compared for each environmental impact aspect separately, and their contribution to

Table 3. Effect table of “thermal soil remediation (in situ)” and “soil excavation and cleaning”.

Effects	Unit	Thermal soil remediation	Excavation
E1 soil quality	1000 cubels	6.08	6.42
E2 groundwater quality	1000 cubels	6.24	6.24
E3 soil loss	m^3	−70	0
E4 groundwater loss	1000 m^3	−6.6	−21.6
E5 energy use	inh.eq	−0.25	−6.27
E6 air emissions	inh.eq	−1.11	−15.32
E7 surface-water emissions	1000 cubels	0	0
E8 waste formation	m^3	−80	−20
E9 space use	m^2.year	−4187.5	−15,000

Note: inh.eq, inhabitant equivalents.

different impact categories can be evaluated. A negative environmental merit score indicates an adverse effect for the environment, whereas a positive score points to an improvement. For both soil remediation technologies, loss of groundwater, use of energy, emissions, generation of waste, and use of space have a negative score, since the soil remediation process has an adverse effect on these impact categories. Soil quality and groundwater quality clearly improve after remediation. When both remediation technologies are compared, it is clear that thermal remediation gives better results for ground water loss, energy use, emissions, and use of space. Soil excavation results in better soil quality and generates less waste. However, the difference in soil quality obtained after applying both remediation options is minimal. There are no emissions into the groundwater, and the loss of soil is minimal (with the thermal remediation technology, a small amount of soil has to be withdrawn in order to insert the installation) or non-existent (with excavation, the contaminated soil is cleaned and can be reused).

Impact assessment

Environmental merit is designed to aggregate several types of environmental costs and benefits into an index, which shows the overall environmental balance of soil remediation (Beinat et al. 1997). For weighing the contribution of each aspect, a panel of environmental experts has been interviewed, and their weights have been used for computing the environmental merit index (E) of REC. The environmental merit of the thermal remediation technology is characterized by an absolute E-value that is three times less than in the case of soil excavation (Figure 3). From an environmental point of view, this technique is selected by the REC model as the best remediation alternative, mainly because of the limited use of space and energy and because it causes fewer emissions.

In Figure 3, "MF reference" represents a hypothetical reference alternative called multifunctional. In this – conservative – alternative using which all polluted soil is cleaned by extraction, and the groundwater is flushed using 50 times the polluted volume (Beinat et al. 1997). This reference alternative scores worse in comparison to the soil excavation and treatment by bioremediation because the extraction process generates a lot of waste, and after extraction, the soil can not be used as soil anymore, whereas reuse of the soil is possible after bioremediation. For the

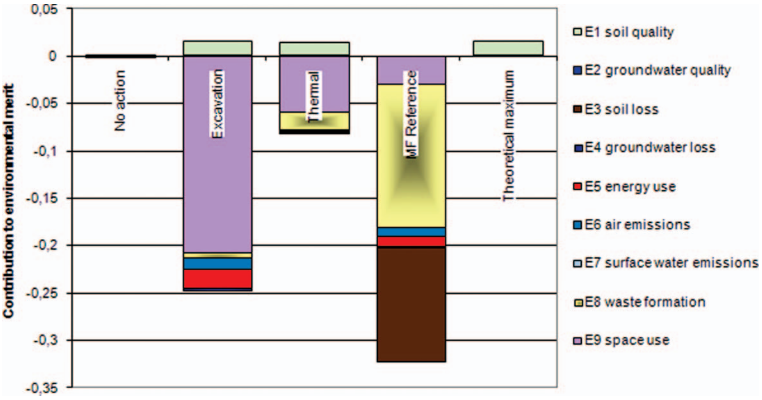

Figure 3. Contribution of each effect, assessed with the REC method, to the environment.

bioremediation process, however, more space is needed in comparison to the cleaning of the soil by extraction.

Selection of a remediation technology based on a BATNEEC analysis

For the BATNEEC analysis, three different scenarios were considered: (1) soil excavation, without consideration of the groundwater remediation (because this can not be assessed using this method, (2) application of the thermal remediation technology (in situ), without consideration of the groundwater remediation, and (3) no active remediation, but monitoring of the groundwater pollution. A score has to be attributed to different criteria in such a way that the sum of the scores for the three remediation options is 15 (Table 4). For example, if the three alternatives are equally good with regard to one aspect (criterion), then each will get a score of 5. The scoring was done by an expert in soil remediation projects. It is clear that the attribution of the scores is subjective and also dependent on the expertise and previous experiences of the evaluator. The only aspect that is quantified in a more objective way is the cost of the remediation, since this is open to precise calculation – at least as an estimate. Therefore, the analysis made by the expert in soil remediation was also made by two other experts of the company, one operating at a senior level with a more economical background, the other at a junior level with a general background in environmental sciences. Their scoring did not significantly differ from the scoring of the first expert. Ideally, decisions about environmental problems ask for a multidisciplinary approach, also involving economists and sociologists in the decision process (French and Geldermann 2005). However, given the difficulties caused by cognitive factors, there is no guarantee that involving a large number of stakeholders from different disciplines will contribute to better decisions than a few experts following sound consultations and assisted by appropriate decision support. Nevertheless, consultations, which introduce the perspectives of the different stakeholders into the analysis, are essential (French and Geldermann 2005).

Despite the fact that the third scenario obtains a good score, it will not be accepted by the Flemish Waste Agency that is responsible for the approval of the soil remediation project, because the Flemish Waste Agency already imposed the remediation of the soil. Therefore, it will not be addressed in this discussion. Nevertheless, this alternative scores best because of the limited nuisance to the environment and its low cost. It can be compared to the "no action" option considered under the REC model.

Globally, in situ thermal soil remediation obtains a better score than soil excavation (Table 4). However, when the environmental aspects group is considered separately, soil excavation performs better than thermal remediation because it obtains a better score to meet the legal objectives (soil and groundwater remediation values) for soil and groundwater quality and for the decrease in the contaminants' content in soil and groundwater. In addition, fewer secondary resources are used during soil excavation because the thermal remediation technology involves a relatively high energy demand. The probability of reaching the legal target values (as imposed by the environmental legislation) for soil and groundwater quality is also high in the case of soil excavation. For the technical aspects, thermal remediation scores better because it causes less nuisance to the environment (e.g. noise, odor, etc.), less damage to the site, since no buildings have to be taken down, and less risk of excavation-induced ground movements. Finally, for the financial

Table 4. Results of the BATNEEC analysis.

Criterion	Weight	Excavation	Thermal soil remediation	Monitoring
Environmental aspects				
Achievement of legal objectives for soil	4.25	8	6	1
Achievement of legal objectives for groundwater	4.25	8	6	1
Decrease of contamination load	4.25	8	6	1
Restrictions for use after remediation	4.25	6	6	3
Use of secondary resources	4.25	3	1	11
Direct emissions to other environmental compartments	4.25	3	3	9
Other adverse environmental effects during remediation	4.25	3	3	9
Duration of the remediation vs. objectives	4.25	7	7	1
Total weight attributed to this criterion	34.00			
	Subtotal	196	162	153
Technical aspects				
Absence of additional nuisance during remediation	8.25	3	4	8
Effective damage due to remediation	8.25	2	6	7
Potential damage due to remediation	8.25	4	5	6
Safety measures to be taken during remediation	8.25	3	5	7
Total weight attributed to this criterion	33.00			
	Subtotal	99	165	231
Financial aspects				
Cost of remediation	22.00	3.65	4.11	7.23
Contamination remaining in soil, groundwater, or both	11.00	7	7	1
Total weight attributed to this criterion	33.00			
	Subtotal	157	167	170
	Total	452	494	554
	Cost in euro	1,436,340	1,265,000	100,000

aspects, the thermal remediation technology scores better, although the difference with excavation and off-site treatment is minimal.

Comparison of the REC and BATNEEC methods

The two assessment methods were compared taking into account several aspects, which include:

(1) Which data are needed as input in the method or model, and how objectively can these data be obtained? In other words, is it possible to objectively quantify the required input? In the BATNEEC method, qualitative information has to be directly transformed into a score by the user, whereas in the REC method, input data are quantitative data, such as energy use and generation of waste. A possible disadvantage of the REC method is that these quantitative data are not always easy to find and that the data inventory is a time-consuming process.

(2) What is the exact result of each method, and how can this result be used? The REC method results in a single score for the REC, whereas the BATNEEC analysis gives a selection of three soil remediation alternatives, with the following information for each option: estimation of cost, expected results, expected environmental impacts (risk for surface and groundwater contamination), and restrictions for land use.

(3) Both assessment tools use their own method to weight scores. The weighting of environmental aspects in the REC method is based on interviews with a panel of environmental experts. In the BATNEEC method, technical, environmental, and financial aspects all have a weight of nearly 1/3, and within the environmental aspects, an equal weight has been attributed to the different categories.

From an environmental point of view, it is clear that the philosophy behind each tool is different, something that also results in different appreciation of environmental effects of the remediation. The BATNEEC method uses a multicriteria analysis that mainly relies on the (subjective) interpretation of the evaluator, whereas the REC model uses real data, which are used to calculate the environmental merit of the soil remediation technology. Of course, one could argue that the weighting of the different impact categories in the REC method is also very subjective, but different evaluators should obtain the same score when they use the same dataset, whereas this it not likely in the case of a BATNEEC analysis.

Other aspects not taken into account by the REC and BATNEEC models

In the past, remediation techniques have mostly been selected without consulting the many stakeholders that are involved in soil remediation techniques, such as local communities affected by the contaminated land and its related remediation operations. “Interactions among all disciplines and stakeholder groups are essential to forge partnerships that will solve environmental problems, rather than deal with only one aspect in isolation” (Burger 2008).

Practitioners and decision makers can rely on a broad range of decision tools that can help them to achieve a better balance between economic, social, and environmental health aspects of contaminated land remediation (Pollard et al. 2004). A holistic approach for the management of contaminated land should ideally include an assessment of the environmental risks of the contamination; an assessment of the environmental, social, and health impacts of the remediation process; and a cost-benefit analysis of the remediation project (Pollard et al. 2004).

Besides addressing the environmental impacts of the remediation activities for a specific site, attention should also be paid to the consequences of reintroducing a remediated site into the economy (Lesage et al. 2007a). Brownfield development and the displacement of economic activities from suburban to urban sites can counteract the phenomenon of urban sprawl.

From a legal point of view, there should be ways to encourage the use of sustainable remediation technologies, together with a disconnection of treated soils from the definition of waste (Wallace 2004).

Finally, the focus should move from remediation, whether sustainable or not, to prevention of soil contamination (Gilmore 2001). Some countries (for example Flanders (Belgium)) have already adapted their environmental legislation, putting greater emphasis on prevention, but a lot is still expected from innovative technological solutions.

Conclusion

Based on a case study, the environmental impacts of two soil remediation technologies, namely excavations and off-site cleaning, which are most often applied in Flanders (Belgium), and a thermal remediation technology based on thermal conduction, have been evaluated. For the analysis, two methods were used, namely the REC (Risk, Environmental Merit and Cost) method, which relies on the principles of LCA, and the BATNEEC method, which is routinely used in Flanders during the establishment of a proposal for a soil remediation project. According to the REC method, the environmental impacts of the thermal remediation technology are lower than of soil excavation and off-site cleaning for the case under consideration, mainly because of the fact that emissions and energy use from the transport of soil and the use of space are lower with the thermal remediation technology. Nevertheless, the final result of the soil remediation, more precisely, the remaining contamination in soil and groundwater, is more uncertain than with soil excavation and off-site cleaning.

Considering the assessment tools that have been used in the present study to select the most suitable remediation technology from an environmental point of view, it is clear that the philosophy behind each tool is different, something that also results in different appreciation of environmental effects of the remediation. Although an LCA-based evaluation method is much more complex and requires much more data than a classical BATNEEC analysis, both evaluation tools could be used in a complementary way. Already in the year 2000, a critical review of tools to asses the environmental effects of the remediation of contaminated land was made by some researchers in the UK (Bardos et al. 2000). They concluded that "the best initial assessment technique will be a qualitative ranking-based approach carried out on a site by site basis. In the longer term, quantitative assessments using LCA and related techniques may be of value" (Bardos et al. 2000). A detailed analysis of some exemplar case studies, as the one presented here, could be helpful to set up a general framework to evaluate remediation options for contaminated sites.

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