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LCA based evaluation of site remediation
Opportunities and limitations

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ABSTRACT

During the last 10 years, several instances have emerged in which a life cycle approach has been applied to the remediation of contaminated sites. A life cycle management (LCM) approach structuring environmental activities and life cycle assessment (LCA) for a quantitative examination, can be helpful for the selection of site remediation options with a lower impact on the ecosystem and human health. Besides addressing the environmental impacts of the remediation activities for a specific site, attention should also be paid to the engagement of different stakeholders and socio-economical consequences of reintroducing a remediated site into the economy.

INTRODUCTION

Selection of site remediation options (1)

Despite the fact that several EU directives support the prevention and cleanup of soil contamination (e.g. EU Directive on Environmental Liability, EU Waste Framework Directive, EU Water Framework Directive, EU Integrated Pollution Prevention and Control Directive), there is no general European directive with regard to Soil Remediation and cleanup. This results for example in inherent differences in soil remediation and clean up values between countries. The selection of the most adequate soil remediation option for a given contaminated site is on its turn not subjected to international regulations and even on national level, only very concise guidelines are provided concerning the choice between different soil remediation options. Whereas some countries rely on the best available technology (BAT), other countries, including Flanders (Belgium), take the best available technology not exceeding excessive cost (BATNEEC) as a criterion for selecting soil remediation options. However, during the last decade, the focus on the most technologically and economically feasible option for soil remediation moved towards other aspects such as the environmental impacts and the socio-economic implications of the soil remediation project.

Green remediation versus sustainable remediation

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 impact of the soil remediation process should also be considered. Green remediation techniques are defined as remediation techniques with a lower environmental impact and a lower associated consumption of natural resources such as water and energy (2). Best management practices for green remediation are complementary to the process used to select primary remedies that best meet site-specific cleanup goals (3). Although mainly one aspect of "sustainability, namely, the environmental aspect, is taken into account, the term "green or gentle remediation" is closely related to "sustainable remediation", which also takes into account social benefits of the remediation, intergenerational risks and engagement of different stakeholders (2).
Sustainable soil remediation can also be addressed from the point of view of the sustainable use of resources. Both soil and groundwater can be considered valuable resources. Ideally, remediation and/or cleaning of soil and groundwater should be performed in a closed-loop system, with conservation of landscape characteristics, to minimize the environmental impact of the remediation project and to achieve the goal of 'sustainable use of soil'.
In the present paper, attention is first paid to the assessment of the environmental impact of the soil remediation process by means of life cycle assessment (LCA) methodology. On the one hand, possibilities of using LCA for the evaluation of soil remediation are illustrated with examples from literature. On the other hand, some additional aspects that should be accounted for in the assessment of the environmental impact contaminated site remediation and that are not or only partly addressed in LCA, are discussed.

EVALUATION OF THE ENVIRONMENTAL IMPACT OF SOIL REMEDIATION BY LCA

Since the 1990's, several tools have been developed to assess the environmental impact of processes and products, such as eco-indicators and other tools based on Life Cycle Assessment (LCA). Since the last decade, LCA has been gaining wider acceptance as a tool for the quantification of environmental impacts.
During the last 15 years, several instances have emerged in which a life cycle approach has been applied to the remediation of contaminated sites. In a literature review, Suér et al. (4) illustrate 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. Besides primary impacts, associated with the state of the site and secondary impacts, associated with the site remediation itself (5) (Figure 1), LCA for contaminated site management should also account for tertiary impacts, associated with the effects of the reoccupation of the site (6). Therefore, different scenarios could be considered and the collection of additional data concerning temporal and spatial effects should be integrated into the evaluation of contaminated sites (4).

An updated overview (Table 1) of case studies dealing with LCA of the remediation of contaminated sites illustrates the high variation in LCA-based evaluation methods that have been used over the last 15 years. Whereas most LCA based methodologies try to express the environmental impact by means of one aggregated score (which is a possibility included in the most recent LCA-packages), some studies rely on characterization indices such as Global warming potential (GWP), acidification potential (AP), eutrophication potential (EP) and photo oxidant creation potential (POCP) (7,8). It is not the purpose of this paper to give an overview of all impact assessment methods. More information on the use of these impact assessment methods for the evaluation of soil remediation can be found in the references provided in Table 1.

In the majority of the LCA-based studies on soil remediation found in literature (Table 1), a comparative LCA is carried out, in which two or more different remediation scenarios are compared (e.g. 21, 22). Most of the existing studies focus on ex situ remediation of contaminated soil, or compare in situ remediation scenarios with ex situ soil remediation. The comparison of two or more in situ soil remediation techniques is the subject of a only few papers (e.g. 11, 21). Several studies indicate that that excavation and ex-situ treatment of contaminated soil consumes more energy and causes more emissions (e.g., 10, 20, 28). However, in situ methods are often more time-consuming and there is a lot of uncertainty with regard to the time frame in which the remediation can be achieved and whether the remediation target will be reached. Additionally, a number of papers compare different LCA based evaluation methods to estimate the environmental impact of a specific site remediation option (27, 28). Suer et al. (27) investigated two impact assessment methods in the evaluation of the environmental impact of the remediation of a site contaminated with ReCiPe 2008 and the environmental product declaration (EPD). Although the outcome of both impact assessment methods was comparable, a good knowledge of both impact assessment methods is necessary for a correct interpretation and comparison of the results. When alternatives for soil remediation are compared, one should also be aware that environmental effects occur on very different environmental problems and geographical scales (18), pointing to the importance of including land use in LCA.

Depending on the impact assessment method used, different environmental impacts are considered. Most impact assessment methods take into account the energy consumption of excavators and other equipment used on site, transport of soil and equipment from and to the site, passenger transport fromand to the site, and the energy demand of remediation installation. The quantity of contaminated soil and groundwater, as well as the amount of groundwater for reinfiltration and the amount of supplemented soil from other

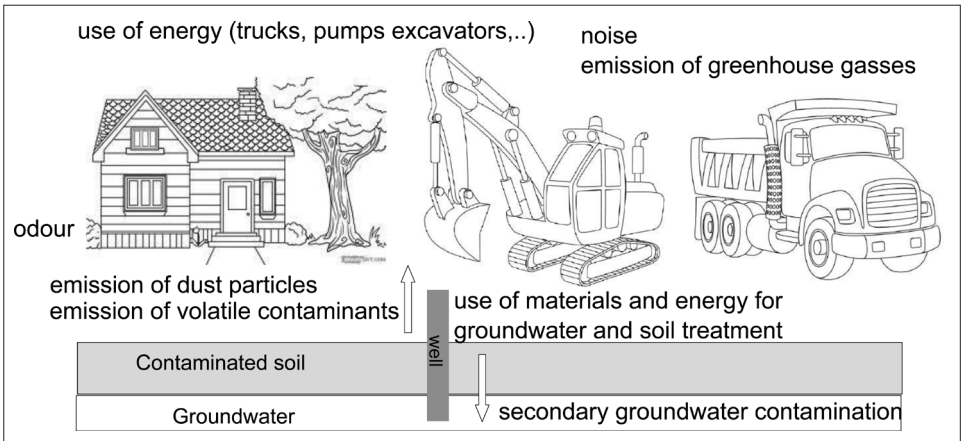

Figure 1. Schematic representation of the main secondary impacts associated with site remediation.

Case study	Applied method or tool	Ref
-	REC (Risk reduction, Environmental merit and Cost)	[9]
Site contaminated with Pb, As, Cd, PAH's	Calculation of potential impact indicators	[10]
Analysis of 6 generic remediation options	Multimedia Maclkay model Solid Waste Burden (SWB) + useable land area	[11]
Site contaminated with mineral oil, PAH and Cr	Use of 'disadvantage factors'	[12]
-	pollution factor (PF) is calculated, and expression of environmental impacts in dimensionless environmental impact units (EIUs)	[13]
Industrial site contaminated with sulfur	No impact assessment but ranking of productivity resources	[14]
Spent pot lining (SPL) landfill contaminated with Cd en Cu	EDIP97 (Environmental Development of Industrial Products) + simulation of contaminant transport in groundwater, using site-specific data	[15]
Diesel-contaminated site	EDIP97	[5]
Landfill sites in Switzerland	Swiss Method of Ecological Scarcity	[16]
Landfill sites in Switzerland	Procedure for estimating heavy metal transport in soil within a current LCA	[17]
Old landfill	Specific method for impact assessment transport of heavy metals	[18]
Former manufactured gas plant site	Characterisation method adopted from UBA (2000)	[19]
Mixed industrial-residential-commercial area with BTEX and THP contamination	IPPC Tier Two methodology	[20]
Brownfield contaminated by human activity in railway sector	IMPACT2002+	[6]
Diesel-contaminated site	US-EPA TRACI (Tool for the Reduction and Assessment of Chemical and other environmental Impacts)	[21]
Industrial site with 300 chemical andpetro-chemical industries	DEcision Support sYstem for REhabilitation of contaminated sites (DESYRE).	[22]
Outdoor shooting range and gasoline station	Decision support tool (DST) based on REC	[23]
Site contaminated with chlorinated ethenes	GaBi4 LCA software and EDIP97 impact assessment method	[24]
Site contaminated with diesel	Global warming potential (GWP), acidification potential (AP), eutrophiation potential (EP) and photo oxidant creation potential (POCP)	[25]
Agricultural fields contaminated with dieldrin	RN_{soil} and economic input-output LCA	[7]
Fyord with dioxin and furan Contaminated sediments	ReCiPe 2008	[26]
Area of 700 km^2 contaminated with Pb, Cd and Zn	Global warming potential (GWP) of CO_2	[8]
Previous oil depot	ReCiPe 2008 EPD (Environmental Product Declaration)	[27]
Distribution centre for new cars	REC	[28]
PCEB contaminated site	IMPACT 2002+, (SimaPro 7.2)	[29]
Former fat processing plant	REC and ReCiPe (SimaPro 7.3)	[30]
Site contaminated by trichloro-ethene (TCE)	EDIP2003 and USEtox	[31]
Site contaminated with PCB	CLM 2001 (SimaPro)	[32]

Table 1 Overview of published LCA-based case studies in which the environmental impact of soil remediation technologies was evaluated (updated after (30)).

locations or soils that will be reused are also mostly considered. In some models (e.g. REC (9)), only the total amount of waste generated (waste soil, wastewater, other waste) is taken into account, whereas other models make a differentiation between different types of waste (e.g. ReCiPe 2008 in (26)). The actual and future land use of the site, is not always included in the same way. Some impact assessment models account for the area occupied during soil remediation, whereas others include the destination of the site after remediation, which actually represents a tertiary impact.

Finally, it is also clear from Table 1 that most case studies deal with sites contaminated with organic contaminants. Sites contaminated with heavy metals (12, 15, 16, 17, 23) or sulfur (14) are only the subject of a few case studies.

LCA is rather complex, data- and time-intensive and requires a proper understanding of impact assessment methods and related software in order to avoid a black box approach. In 2000, a critical review of tools to assess the environmental effects of the remediation of contaminated land was made by some researchers in the UK (33). They recommended to first make an initial ranking of soil remediation techniques based on more qualitative site-specific criteria. In a second step, a quantitative assessments using LCA and related techniques may be of value for an in-depth analysis. A preliminary selection or ranking of remediation technologies could for example rely on a BATNEEC analysis (28), which is based on the principles of a multicriteria analysis.

The SuRF (Sustainable Remediation Forum) report (40) provides some guidelines and indicators that can help to select the most 'sustainable' soil remediation options. For this purpose, three categories of indicators are established (environmental, social and economic indicators). The environmental indicators that best take into account the differing perceptions and technical perspectives of the stakeholders involved in the evaluation and selection of the most appropriate remediation technologies, could be used for a preliminary selection of remediation options (34). For the final selection, the most feasible remediation options can be subjected to a LCA.

OTHER ASPECTS NOT OR ONLY PARTLY ADDRESSED IN LCA (1)

Monetary valuation of the consequences of site remediation

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 (35). A holistic approach for the management of contaminated land should ideally include an assessment of the environmental risk of the contamination, an assessment of the environmental, social and health impact of the remediation process and a cost-benefit analysis of the remediation project (35). In most remediation projects, a cost-benefit analysis is already carried out. Whereas the benefits for the environment and human health are well quantified in LCA, they are seldomly expressed in monetary terms and thus not systematically included in the cost-benefit analysis.

Morais and Delrue-Mathos (36) emphasize that the environmental effects of a site after remediation are often disregarded, which may lead to misleading conclusions. Ideally, all stakeholders should agree on the boundary conditions of the LCA, such as the exclusion of capital equipment and on the way multifunctional processes are dealt with.

Ecosystem services to define the goal of the remediation project

The relative sustainability of a soil remediation project also depends on the objectives of the remediation (2), so that it is not possible to give an overall 'sustainability score' to a specific soil remediation technique. More and more, the concept of 'ecosystem services ' is taken as a starting point to determine the goal of a soil remediation project. Ecosystem services can be defined as the resources and processes that are supplied by natural ecosystems. Cleanup activities can modify ecosystem services, so the determination of ecosystem services is important to avoid unwanted negative effects of soil remediation operations. Ecosystem health is quantified in LCA by linking inventory systems to so-called impact categories. During the last decade, developments in Life cycle analysis have resulted in the definition of so-called mid-point impact categories, such as ecotoxicity and global warming potential. These indicators are characterized by a relatively low uncertainty and a relatively easy interpretation. End point indicators such as biodiversity have to deal with a lot of uncertainty, which should also be accounted for in LCA (37). However, the ecosystem services approach requires a deep knowledge of the site in terms of biodiversity, which is not the main focus of the LCA approach

Impact assessment methods for human health and ecotoxicity

Besides the estimation of contaminant emissions (data inventory faze), fate and exposure modeling and the assessment of ecotoxic effects are essential issues. At the moment, there is no consensus regarding soil quality in the EU. A variety of risk assessment tools is used to assess the risk of contaminated soils towards human health and ecosystem health (38).

Initially, the assessment of the global impact on terrestrial ecosystems within life cycle impact assessment was limited to the impact on soil organisms only because terrestrial vertebrates require a complex modeling that requires data on toxicity upon terrestrial vertebrates and the multiple exposure pathway that should be considered (39). During the last few years, several impact assessment methods for human health and ecotoxicity have been developed. Pizzol et al. (40) give an overview of different impact assessment methods of heavy metals on human health, but conclude that LCA practitioners should choose each model which has the highest consensus with regard to their specific problem. In the US, the USEtox model is recommended for human and eco-toxicity LCIA, but it is not integrated in any complete LCIA method yet.

For organic contaminants, changes in concentrations over time, such (bio)degradation, volatilization, are taken into account in risk assessments. However, when evaluating groundwater impacts, attentionshould also be paid to potentially degradable contaminantsforming metabolites of higher human toxic concern than the parent compound (41). For heavy metals, total concentrations in soil are mostly used as an input in risk assessment models. However, heavy metals in contaminated soil are rarely released completely, as only a portion of heavy metals is "bio-available" or "geo-available" (which means that the metals can be released and become available for biological uptake). For remediation projects for soils and sediments, this is of course an important consideration, since only a portion of the total metal load in soils or sediments can be considered as 'geo-available' or mobile. In a risk-conservative approach, it is assumed that all the metals contained in a solid matrix (soil, sediment, waste material, etc.) will be released. When this 'total metal content' is used as an input in LCA analysis, this will most likely result in an overestimation of the risk associated with the heavy metals. Additionally, LCA typically covers an extended period of time (depending on the life cycle of a product or process), so long-term heavy metal emissions have to be assessed. The assessment of heavy metal release from soils and sediments on the long term is still controversial. Several methods and procedures have been proposed to estimate the long term emissions of heavy metals contained in soils, sediments and waste

materials, but there is no consensus on which method performs best (42).
Finally, Lemming et al. (41) indicate that only few life cycle assessments have been conducted for in situ remediation of groundwater contamination. Therefore, more attention should be paid to the inclusion of toxicity via groundwater as an impact category.

CONCLUSION

Life cycle assessment (LCA) is a useful tool to generate information on the environmental impacts of soil remediation technologies. In the last decade, many different impact assessment methods have been applied to assess the environment impacts of site remediation, mainly for sites with an organic soil and groundwater contamination. LCA is rather complex, and requires an understanding of impact assessment methods and related software in order to avoid a black box approach. Therefore, it should be considered as a complementary tool to be used for an in-depth analysis of soil remediation alternatives that have been previously selected Finally, several other aspects, such as monetary valuation of remediation methods and the impact assessment for human health and ecotoxicity are important to take into account in the further development of LCA at a tool for the evaluation of site remediation.

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