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Environmental Impacts of Contaminated Site Remediation

- A Comparison of two Life Cycle Assessments

Jenny Andersson

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LINKÖPINGS UNIVERSITET

Linköpings universitet, Campus Norrköping, SE-601 74 Norrköping, Sweden

Institution, Avdelning
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Title
Environmental Impacts of Contaminated Site Remediation
- A Comparison of two Life Cycle Assessments

Författare
Author
Jenny Andersson

Sammanfattning
Abstract

The decision process of which technique to choose for remediation of contaminated sites has traditionally focused on the clean up level, the time required and the economical resources. The environmental costs of the remediation are seldom taken into consideration. With a Life Cycle Assessment (LCA) it is possible to receive an overall picture of the environmental impacts caused by a remediation technique. In this thesis a comparison of two LCA methods has been made. The methods are named REC and Uva and are used in the Netherlands and Germany. Two remediation techniques, the adsorption technique and the bioremediation technique, were compared and data from a discontinued petrol station were used. The output from the REC method indicated that the adsorption technique causes more environmental costs then the bioremediation technique. The main reason is because the adsorption technique consumes more groundwater and energy. The UvA method presented a different result. According to this method the bioremediation technique causes more environmental costs. This is because the bioremediation technique consumes more energy and causes more emissions. The main reasons of the difference between the REC and the UvA methods are that they use diverse ways to calculate the consumption of energy, have different system boundaries and consider different impact categories. A conclusion of the present study is that a decision process of which remediation technique to use at a contaminated site could be dependent on which method is used as a decision support tool.

Nyckelord
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1 INTRODUCTION

The evolution of modern society has resulted in the development of urban areas and an increase in material wealth for the majority of the population. An inevitable characteristic of this development is contamination of air, water and soil. An effect of the contamination is different environmental problems and contaminated sites are one of the problems due to the development of the modern civilisation.

A contaminated site is defined as an area, which is so contaminated by a point source, that concentrations substantially exceed regional background levels (Swedish Environmental Protection Agency, Swedish EPA, 1999). The point sources are generated from several activities within the industrial, agricultural, commercial and domestic sector. The sites are contaminated to various degrees by several chemicals or pollutants and exist in a number of geographical locations (Asante-Duah, 1996). It is estimated that there are more than 750 000 contaminated sites in Europe (ScanRail Consult et al., 2000a), and according to the Swedish EPA (2003) approximately 40 800 of them are located in Sweden.

Contaminated sites provide environmental risks in their immediate surroundings, and contaminant releases from the sites can cause adverse effects to humans and other organisms. The sites also contribute to the long-term contamination of soil, groundwater and food chain. Therefore it is important that the sites are managed effectively. The risks to humans and ecosystems in the immediate surrounding can be reduced by a remedial action and there are many existing techniques appropriate for remediation of organic and/or inorganic substances (Asante-Duah, 1996).

The objectives with a remediation action are to reduce the contaminated substances and to gain environmental benefits like future land use and cleaner ground water and surface water, but the remediation also causes negative environmental impacts. These environmental costs consist of consumption of energy and material resources and discharges of substances to the surroundings. The effects of these environmental costs are for example scarcity of resources, acidification and global warming (ScanRail Consult et al., 2000b).

The decision process of which technique to choose for the remedial action has traditionally focused on the clean up level, the time required and the economical resources. The environmental costs of the remediation are seldom taken into consideration in the decision process (ScanRail Consult et al., 2000b). A method with a higher clean up level compared to another method is not necessarily the method which has the lowest environmental impacts. Environmental costs should therefore be included in the decision support tool to receive a more comprehensive view of the remediation techniques (Ribbenhed et al, 2002). Several approaches, which include the environmental perspective, have been developed and some of the most common are: Environmental Impact Assessment (EIA), Multi Criteria Analysis (MCA) and Life Cycle Assessment (LCA) (Shakweer and Nathanail, 2003). This thesis will focus on the LCA approach.

An LCA is a scientific method, which makes it possible to get an overall picture of the environmental impacts caused by a remediation action. It is also possible to compare environmental impacts from different remediation techniques. The LCA method follows a cradle-to-grave approach, which means that it includes the environmental impacts during the entire life cycle of a product (Ribbenhed et al., 2002).

Methods based on a life cycle thinking for soil remediation have been developed in the Netherlands, Germany, US, Canada and Denmark (Suèr and Nilsson-Påledal, 2003). The method developed in the Netherlands is named REC. The REC method includes three perspectives: risk assessment, environmental merit and costs. The German method is called UvA. It includes an evaluation of the secondary impacts of a remediation action and it is a complement to a risk assessment (Volkwein et al., 1999). Sweden has not yet developed a similar method (Suèr, 2003, personal communication).

The LCA methods for assessing environmental impacts caused by remediation of contaminated sites differ from each other in for example the delimitations of the LCA, the environmental impact categories and input data requirements. The results may be dependent on which method is used. In order to get a further insight and improve the methods, a comparison between different LCA methods using the same case study is needed (Suèr and Nilsson-Påledal, 2003).

1.1 The Aim of the Thesis

The overall aim of this thesis is to compare two different methods, which have been developed for the evaluation of environmental impacts caused by remediation of contaminated sites. Both methods are based upon life cycle assessment thinking. The methods studied in this thesis are the REC method and the UvA method. Applying the methods to a former petrol station made the comparison possible. The comparison leads to an evaluation and a further insight into the methods for assessment of environmental impacts.

The aim is specified further through the following questions:

- In what way are the results from the methods different?
- How are the indata requirements different between the methods?
- How do the delimitations in the methods affect the results
- How are the impact categories different between the methods?

1.2 Overview of the Thesis

This thesis is divided into six chapters. After the *Introduction*, the four steps in an LCA are presented in chapter two. The third chapter*, The REC and UvA methods,* describes the two LCA methods used in this thesis. In chapter four the methodical framework of how the comparison between the methods was done is outlined. It also gives an explanation of the case study and the data used in the methods. Chapter five, *Results and Discussion,* presents the outputs of the methods. Some factors, which have an effect of the results are also presented and explained. The last chapter gives concluding remarks and the main finding of this thesis.

2 THE LCA FRAMEWORK

LCA is a system analysis method, which aims to get an overall picture of a complex system. The method assesses the environmental impacts of a product by identifying and quantifying energy and material use. Products in this context signify materials, products and services. The LCA method considers the whole life cycle of the product, from extraction of resources, transports and manufacturing to distribution, use and waste management. The results from the method can be used to identify where the largest hot spots in the life cycle of a product are (Ribbenhed et al, 2002).

An LCA is used as a decision support tool by authorities, companies and Non Governmental Organisations. Much is expected from the method, but the results are also being criticised (Finnveden, 1998). An advantage with the LCA method is the capacity to handle big sets of data, but finding the required data for the method is often a problem. In many cases the available data from a product are based on short time series or produced for another purpose. The lack of high quality data has a significant impact of the LCA results and the results should therefore bee seen as estimations instead of precise values (Lindahl et al., 2000). An additional advantage with the LCA method is the possibility to study how alternative materials and technologies reduce or increase the environmental impacts of the product (Ribbenhed et al., 2002).

An encountered criticism of LCA is that comparative LCAs sometimes lead to apparently contradictory results. It is often difficult to understand the reasons for the difference in the results. This is because the LCA methods are complex systems (Finnveden, 1998).

During the past years there has been a development of the methodology of LCA and as a result of this a common framework and terminology has emerged. Several guidelines have been published and one of them is "The Code of Practice", developed by SETAC (Society of Environmental Toxicology and Chemistry). Standards for the LCA have also been developed by ISO (International Standard Organisation) (Finnveden, 1996).

An LCA is often divided into four steps; goal and scope definition, inventory analysis, impact assessment and interpretation (Finnveden, 1996). The following sections give a short explanation of each step and describe how to use an LCA in a remedial project.

2.1 Goal and Scope Definition

The first step of the LCA describes the objectives of the study, functional unit, the limitations and the data quality requirements (Bender et al., 1998). The way to perform a LCA is dependent on the purpose of the study. Therefore it is important to explain the reasons for conducting the LCA and in which context the results are going to be used (Ribbenhed et al., 2002).

The functional unit should be identified in this first step. The functional unit is defined as "the service or function on which alternative products are to be compared" (Shakweer and Nathanail, 2003). When comparing alternative remediation strategies it is according to Shakweer and Nathanail (2003) appropriate to choose the functional unit as one unit of the input (i.e. mass of contaminated soil). The reason for choosing a functional unit of the input instead of the output (i.e. ”clean” soil) is that output from different remediation strategies does not have the same concentration of contaminated substances. The output is therefore an unfair unit for comparing remediation strategies.

The delimitations consist of a clarification of the system boundaries, the allocations of the consumption of materials and resources, the criteria for data quality and choice of valuation method. An example of a limitation is whether the resources for the production of machineries are included in the methods or not. The limitations create a simplified model of the contaminated site and the limitation is a compromise between gaining a realistic model as possible and the work required for collecting data (ScanRail Consult et al., 2000b).

2.2 Inventory Analysis

In the inventory analysis, the relevant inputs and outputs from the defined system are calculated. The data covers the flows of materials and resources in all phases during the life cycle of the product. This often involves extensive data sets and calculations and therefore the inventory analysis is the most time consuming step (ScanRail Consult et al., 2000b).

2.3 Impact Assessment

The impact assessment is divided into three subcomponents with the overall aim to evaluate the results from the inventory analysis. The first subcomponent is ***classification*** in which the different inputs and outputs from the inventory analysis are assigned to a number of impact categories. The impact categories are based on the expected impacts in the environment. The next subcomponent is ***characterisation*** in which the potential contribution of each input and output are assessed to different environment impacts. The characterisation should also answer the question: What is the total potential contribution of the system to different environmental impacts? (Finnveden, 1996)

The last subcomponent is ***valuation.*** This is the step where the relative importance of the environmental impacts is weighted against each other. Several methods for valuation have been developed and the weighting procedures are often based on different principles. The weighting process could, in REC for instance, be based on an expert panel, which are asked about their opinion. It could also be based on “the willingness to pay” or “the distant to target” principle. The willingness to pay is built upon the willingness to pay in order to avoid something. The distance to target principle is relating the valuation to some sort of target (Finnveden, 1996). Today there is no international consensus of which valuation method is the best to use (ScanRail Consult et al., 2000b).

2.4 Interpretation

In this step the results are interpreted into conclusions and recommendations in line with the defined goal and scope with the study (Scan Rail Consult et al., 2000b).

3 THE REC AND UVA METHODS

Management of contaminated sites requires a number of decisions about technical, economical, environmental and social concerns (Bardos et al., 2001). Decision support tools are developed to help those who take the decisions in the area of contaminated sites. During the past year several tools have been developed and are in form of written guidance and/or computer software (CLARINET, 2002). The aim of the decision support tool is to obtain a transparent and reproducible approach. The tools are also used to compare contamination issues at different sites (Bardos et al., 2001). The need for decision support tools is widely recognised but the tools have discovered to have varying degrees of success in practical use (CLARINET, 2002).

LCA is a method, which can be used to assist the environmental decision-making in contaminated site remediation (CLARINET, 2002). Both the UvA and REC methods are software tools created to compare different remediation techniques for contaminated sites (Volkwein et al., 1999). The following sections give a more detailed explanation of the methods.

3.1 The REC Method

Beinat and co-workers developed the REC method in the Netherlands (Volkwein et al, 1999). The word REC is an abbreviation of ***R***isk reduction, ***E***nvironmental merit and ***C***osts, which are the three perspectives, included in this method. The method makes it possible to seek for balance between the three perspectives (IVM, 2003).

The risk reduction perspective, which includes the local effects, calculates the degree in which the remedial action reduces the risks for humans and ecosystems. The remedial action is compared to a "without action" alternative and the difference between these alternatives is the degree of risk reduction. The environmental merit illustrates the balance between environmental benefits and cost. Environmental benefits from a remedial action are for example the increase of clean soil and groundwater. Waste and water pollution are example of environmental costs. The higher score a remediation action gets, the more the environmental benefits are. There are nine major categories under which inventory data is classified and a panel of experts has been used to decide the relative importance of each category (IVM, 2003). The eight people in the panel are experts in environmental science and soil science in the Netherlands (Drunen et al., 2000). The third perspective, costs, gives an indication of the total costs necessary for all phases of the remedial action (IVM, 2003).

3.2 The UvA Method

The UvA (Umweltbilanz von Altlastensanierungsverfahren) method was developed for the federal state of Baden-Württemberg, Germany. The method has a more detailed life cycle assessment approach than REC, but the method neither includes a risk assessment nor the consideration of the remediation costs. The UvA method should therefore be seen as a complement to a risk assessment in order to receive a more comprehensive picture of the environmental impacts of the remedial action (Volkwein et al, 1999).

In the UvA method the materials and energy used for the remedial action are translated into a list of predefined modules. The method consists of about 60 modules and every module is related to generic data sets (Bender et al, 1998). Average data is used in the data sets and most of the data are adjusted to the conditions in Western Europe, but some of the data are related to a global scale. Every remediation technique is modelled with these modules (Volkwein et al, 1999).

The results from the inventory analysis are presented in a Life Cycle Inventory Table. The inventory data is then classified in ten major impact categories. To facilitate the interpretation between the remediation techniques the difference are presented in a table with disadvantage factors. A disadvantage factor is the quotient of the higher and lower value (Volkwein et al, 1999).

4 METHOD

The reason for choosing to compare two LCA software tools is to study if different methods give different result. According to Bardos et al. (2001) a limitation with software tools is that the decision makers tend to accept the results as being correct. Therefore it is interesting to study if a decision of which remediation technique to use on a contaminated site could be dependent of the decision support method that is used.

In this thesis a comparison between the REC and the UvA method is done. The REC method, the UvA and a Danish method, Evaluation and Optimising of Contaminated site remediation[1], were available at the Swedish Geotechnical Institute. The reason for not choosing the Danish method was because the method required more indata than the other two methods. The required indata were not available in the case study so if this method were to be used, a lot more assumptions had to be made.

Using data based on a case study, assumptions and theoretical calculations made the comparison of REC and UvA possible. The assumptions and theoretical calculations were made by reading literature as well trough communication with experts about remediation techniques. The same assumptions are made in both methods and therefore the assumptions and theoretical calculations do not have a significant impact on the results of the comparison. However, the results should not be seen as a result of the environmental impact caused by remediation of the site in the case study. This is because the remediation techniques have been modified in this study (see 4.1.1). The results from the different methods were first evaluated separately, followed by a comparison of the results and the methods. The next sections describe the case study, the input data and the analysis of the results and the methods.

4.1 Case Study

The case study is a discontinued petrol station in Sweden. The reason for choosing this case study is that there is many contaminated petrol stations in Sweden. Many of the sites are going to be remedied and therefore it is interesting to study the substances and techniques, which may be used for the remediation.

The petrol station was discontinued in 1980. There are a residential building and a car repair shop on the estate. The estate also comprises two underground cisterns for petrol and the area of the site is 2000 m^2 (SGI, 2000). The soil was contaminated by PAH (polycyclic aromatic hydrocarbons) and aliphates. The concentrations for these substances were below the guideline values for remediation of contaminated petrol stations, formulated by the Swedish EPA (1998). The groundwater was contaminated by aliphates, BTEX (Benzene, Toluene, Ethyl benzene, Xylene) and PAH. The concentration of aliphates was above the guideline values and the concentrations of BTEX and the PAH was below the guideline values (SGI, 2000).

A decision was made to treat the groundwater, in order to be able to use the water for irrigation. The groundwater was cleaned with the ***pump and treat*** technique. The water was pumped from a well and then pumped through a filter, where the contaminants adsorbs .The treated water was released in a ditch. The remediation action was not sufficient to reduce all

[1] DSB, Banestyrelsen, MiljØstyrelsen and EU Life developed the method.

contaminants and therefore the water was treated again with the ***in-situ bioremediation*** technique. The water was pumped from the well and nutrients and electron acceptors were then added to the water (SGI, 2002). The nutrients and electron acceptors stimulate the microorganisms to destruct the contaminants and the end products of the destruction are carbon dioxide, water and salts (Bedient et al, 1999). The water was reinfiltrated into the soil after cleaning (SGI, 2002).

4.1.1 Delimitations of the Case Study

The groundwater in the case study was contaminated by aliphates, BTEX and PAH (SGI, 2000). This thesis only considers aliphates. The reason for choosing aliphates was that it was the contaminant with concentrations above the guideline values. Another reason is that most of the fuels contain aliphates. As a result of this aliphates are a common contaminant in areas contaminated by petrol stations (Larsson and Lind, 2001).

The remediation techniques were modified from the case study, in order to fit the aim of the thesis. The techniques in this study are seen as separate techniques, which means the study consider what will happen if the first technique ***or*** the second is used. The assumption that the techniques reduce the same amount of aliphates during the same period of time is made.

The first technique is named ***adsorption*** and the second is named ***bioremediation***. The adsorption alternative comprises pumping water from a well and then pumping it through a filter with activated carbon. When using the bioremediation technique some of the water is pumped from the well and sodium nitrate and hydrogen peroxide are then added into the water. Then the water is reinfiltrated into the soil.

4.2 Data Input for the REC method

The REC method comprises three perspectives. In this study only the environmental perspective is taken into consideration. This is because the aim of this thesis is to study the environmental impacts, and not the costs or the risk reduction, of a remediation action. The uncertainty analysis within the environmental perspective is not included in this study. The data used in the REC method are presented in table 1. The data in the table are based on the case study and assumptions. The headings *Current situation* and *Treatment category* describe in which part of the method data are used.

Table 1: Data input for the REC method. The data are based on a case study and assumptions. The headings *Current situation* and *Treatment category* describe in which part or the method the data are used.

Data category	Adsorption	Bioremediation
Current situation		
Quality objective (µg/l)	100	100
Intervention value (µg/l)*	100	100
Concentration of aliphates (µg/l)	200	200
Volume of contaminated groundwater (m^3)	200	200
Treatment category		
Load (m^3.year)	0,00001	0,00001
Consumed groundwater (m^3)	200	50
Volume of groundwater to pump (m^3)	200	50
Lifting height (m)	6	6
Volume groundwater to treat (m^3)	200	200
Waste (m^3)	0,0018	-
Land use (m^2)	5	5
Time requirement for remediation (year)	0,5	0,5

* Value to evaluate the risks of contaminated sites (Guideline value).

Load is a variable, which is based on the volume of contaminated groundwater, the remediation period and the concentration of hazardous substances. In this study the volume of groundwater is determined to 200 m^3 and the remediation period to 0.5 years. The concentration of aliphates is 200 µg/dm^3 before the remediation and 100µg/dm^3 after the remediation. The concentration of aliphates after remediation is the same as the Swedish EPA (1998) guideline values for contaminated petrol stations. The calculations within *Load* are the same for both techniques. The rest of the data in the table are based on assumptions.

4.3 Data Input for the UvA method

The UvA method consists of several modules and every remediation technique is modeled with these (Volkwein et al., 1999). In this study the adsorption alternative is modeled with the modules *Grundwasserhydraulik* (pumping the water) and *Grundwasserreinigung-adsorption*" (treatment method). The bioremediation alternative is modeled with *Grundwasserhydraulik* and *Mikrobiologische- grundwasserreinigung in situ* (treatment method). The data used in the Uva method is presented in table 2.

Table 2: Data input for the UvA method. The data are based on a case study, assumptions and calculations

Data category	Adsorption	Bioremediation
Risk (before remediation / after remediation)		
Relevant risk (Maßgebliches Risiko)	5,3 / 4	5,3 / 4
Unsecured area	10,3 / 4	10,3 / 4
Area of the site (m^2)	2000 / 0	2000 / 0
Volume of contaminated groundwater (m^3)	200 / 0	200 / 0
The site is used as:	Residential area	Residential area
Demands		
Workdays to build the equipments	3	3
Time requirement for the remediation (days)	180	180
Average density of the soil (t/m^3)	1,8	1,8
Distance to settlement (m)	100	100
Land use (m^2)	5	5
Volume of soil to treat (m^3)	1	1
Volume of groundwater to treat (m^3)	200	200
Hydraulic pump		
Running time (days)	180	180
Pump rate (m^3/h)	0,05	0,01
Lifting height (m)	6	6
Reinfiltration (%)	0	100
Adsorption		
Total mass of hazardous substances (kg)	0,04	-
Concentration capacity of activated carbon (%)	5	-
The activated carbon after use is:	Disposed	-
Bioremediation		
Running time (days)	-	180
Sodium nitrate ($NaNO_3$) (t)	-	0,0005
Hydrogen peroxide (H_2O_2) (kg)	-	0,1

The data in table 2 are based on data from the case study, assumptions and theoretical calculations. The assumptions included in the data have been kept as similar as possible to the REC case. The data in the table are here explained further:

- *Risk*

The *Relevant risk* and the *Unsecured area* are variables, which describe the risk levels. According to Volkwein et al (1999) an acceptable risk level after a remediation action is 4 and therefore 4 is used as a risk level in this study. The values for the risk levels before the remediation are based on an example in the UvA method. In this study the variables *Relevant risk* and *Unsecured area,* have been changed in order to investigate if the variable has an impact of the results. The values 2, 4, 5,3 and 10,3 were entered in the UvA method and the same values were checked for both variables. These changes did not have a significant impact of the results.

- *Demands*

The data in this section are based on the case study. The variable, *Volume of soil to treat,* was determined to 1 m^3 for both methods. This is because it is not possible to choose 0 as value.

- *Hydraulic pump*

The pump rate within the adsorption technique is based on the assumption that all groundwater is pumped and the pump rate within the bioremediation technique is based on the assumption that 50 m^3 of water is pumped.

- *Adsorption*

The total mass of hazardous substances was calculated based on the concentration of aliphates (200 µg/dm^3) and the total volume of water. The reason for choosing 5 % as concentration capacity of the activated carbon is that it is a common capacity according to the UvA method.

- *Bioremediation*

The amount of sodium nitrate and hydrogen peroxide for the bioremediation technique is based on theoretical calculations. Assumptions that the chemical form of aliphates is $C_{10}H_{22}$ are made in the calculations. Another assumption is that 50% of the nitrates added are used for building up new cells in the microorganisms. These calculations and assumptions were made with help from Lennart Larsson at the Swedish Geotechnical Institute (2003).

4.4 Analysis

An LCA is a system analysis method (Ribbenhed et al, 2002). The overall aim with a system analyse is to obtain a holistic view of a complex system. The system is studied by creating a model, which gives a simplified picture of the system. The models can be created with different system boundaries, which may have an impact of the results of the analysis (Gustafsson et al., 1982). According to Ryding et al (1998) there are several types of system boundaries. Some of them are:

- *Boundaries to nature systems.* These boundaries indicate in what degree the extraction of energy and resources are included in the LCA

- *Boundaries to production capital and staff,* These indicate if the environmental impacts due to the manufacturing of for example machineries, roads and means of transport are included in the LCA

- *Time horizons;* indicate the time frame in the LCA.

In this thesis a comparison of two LCA methods was done. The REC and the UvA methods have different system boundaries. The overall aim of the comparison of the methods is to study if and how the system boundaries and other factors have an impact of the results.

In present study an evaluation of the methods were first made separately. A comparison was done of how and why the remediation techniques were different within the method. The differences were studied by comparing the remediation techniques in every step (i.e. inventory analysis, impact assessment) of the LCA method, followed by a summarising interpretation of which remediation technique causes the most environmental costs. Secondly, the results from the methods were compared to each other. During the comparison system boundaries and other factors that were different between the methods emerged. The system boundaries and factors that appeared to have an impact on the results in this study were energy consumption, emissions, system boundaries to production capital and additives, impact categories and weighting methods. These boundaries and the factors were investigated further and the results were related to other studies.

5 RESULTS AND DISCUSSION

The outputs of the methods are first presented, explained and discussed separately, followed by a comparison between the results and the methods. In the end of the chapter, there is a discussion about the methods as decision tool for sustainable development.

5.1 The REC Output

5.1.1 Inventory Analysis

The first output of REC is an inventory table, which describes the consumption of energy and resources, waste and emissions caused by the remediation action. The table illustrates the differences between the adsorption remediation technique and the bioremediation technique. The output is shown in table 3.

Table 3: Data of consumption, waste and emissions for two remediation techniques in the REC method

Consumption category	Unit	Adsorption	Bioremediation
Soil quality	kubels*	0	0
Groundwater quality	kubels*	200	200
Consumed soil	m^3	0	0
Consumed groundwater	m^3	-200	0
Energy (total)	kWh	- 39	- 26
-Energy (pump)	kWh	-17	-4
- Energy (treatment process)	kWh	-22	-22
Air emission	inw.eq**	-0, 003	-0, 002
Water emission	kubels*	0	0
Waste	m^3	-0, 002	0
Land use	m^2.year	-2, 5	-2, 5

**A kubel is a unit, which is calculated by multiplying the volume of contaminated water with the middle value. The middle value is a mean value of the Quality objective and the Intervention value, in this case is the middle value 100µg/l*

** Inw.eq = *0, 0219*consumption of electrical energy (GJ) + 0,0074 * consumption of diesel (GJ)* (Drunen et al., 2000)

Some of the results in the table have positive values while other have negative values. The positive values are the factors, which after remediation, contribute to environmental benefits. The negative values are the factors that cause environmental costs. Table 3 shows that the only factor which has a positive value is *Groundwater quality*. This is because the remediation action leads to a higher quality of the groundwater. The higher score in the *Groundwater quality* category, the higher quality of groundwater after remediation.

In the category *Consumed groundwater* the adsorption technique shows a higher negative value than the bioremediation technique. This is due to the fact that the groundwater is released in a ditch after treatment. In the bioremediation technique all groundwater is infiltrated back into the soil after treatment, and therefore the groundwater is not consumed.

The adsorption alternative also shows a higher negative value in *Waste*. The waste is the activated carbon, which is used as a filter. The bioremediation method produces no waste.

The total consumption of energy is higher for the adsorption alternative than the bioremediation alternative. This is because the adsorption technique consumes more energy when pumping up the groundwater. All groundwater is pumped up in the adsorption technique and therefore more energy is consumed. For the treatment process the consumption of energy is the same for both techniques. The amount of energy consumed, for the treatment process, seems only to be based on the volume of contaminated water. Since the adsorption and bioremediation techniques have the same consumption of energy in the treatment process, what remediation technique that is used for the cleaning process do not have an impact of the energy consumption.

The air emissions are based on the consumption of energy. The air emissions, which are included in the REC method, are CO_2, NO_X and SO_2 (Drunen et al., 2000). Table 3 shows that the adsorption technique consumed more energy than the bioremediation and therefore the air emissions are higher for the adsorption alternative.

As a complement to table 3 the REC method presents a figure, which facilitates the comparison between the remediation techniques (figure 1). The figure shows in which categories the adsorption technique causes more environmental costs than the bioremediation technique. The results are presented in normalised values.

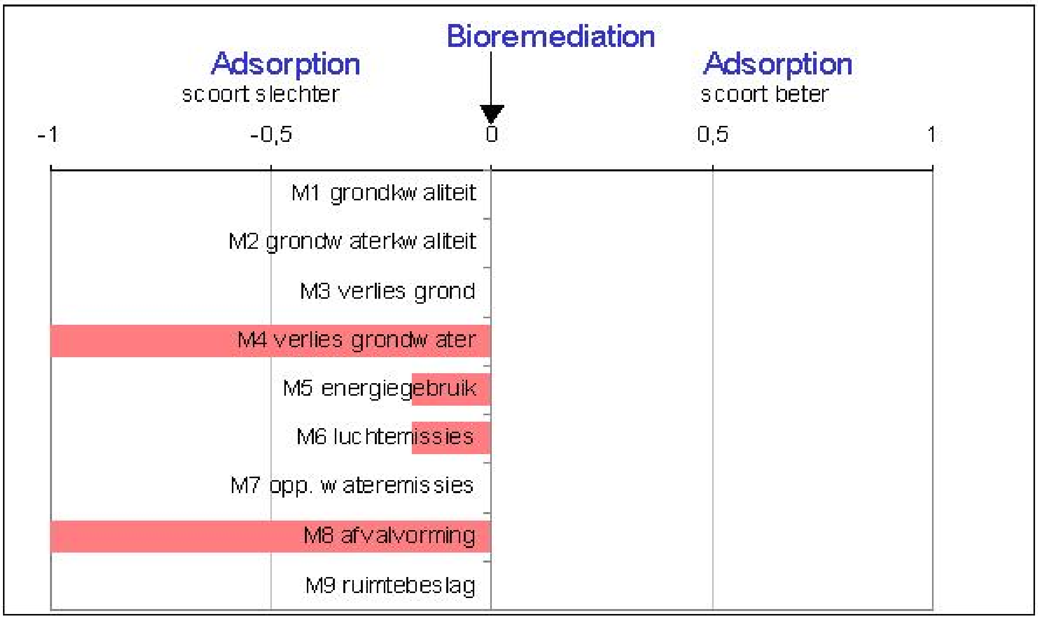

Figure 1: Comparison between the remediation techniques in normalised values.

Figure 1 shows that the categories in which the adsorption alternative shows more environmental costs are *Consumed groundwater (verlies grondwater), Energy (energiegebruik), Air emissions (luchtemissies)* and *Waste (afvalvorming)*. The techniques have the same environmental impacts in the other categories.

5.1.2 Impact Assessment

In the REC method the results of the inventory analysis are weighted in the impact assessment. The weighting process is based on the opinions of an expert panel (IVM, 2003). Every impact category has a weighting value. The results of the weighting process are presented in figure 2.

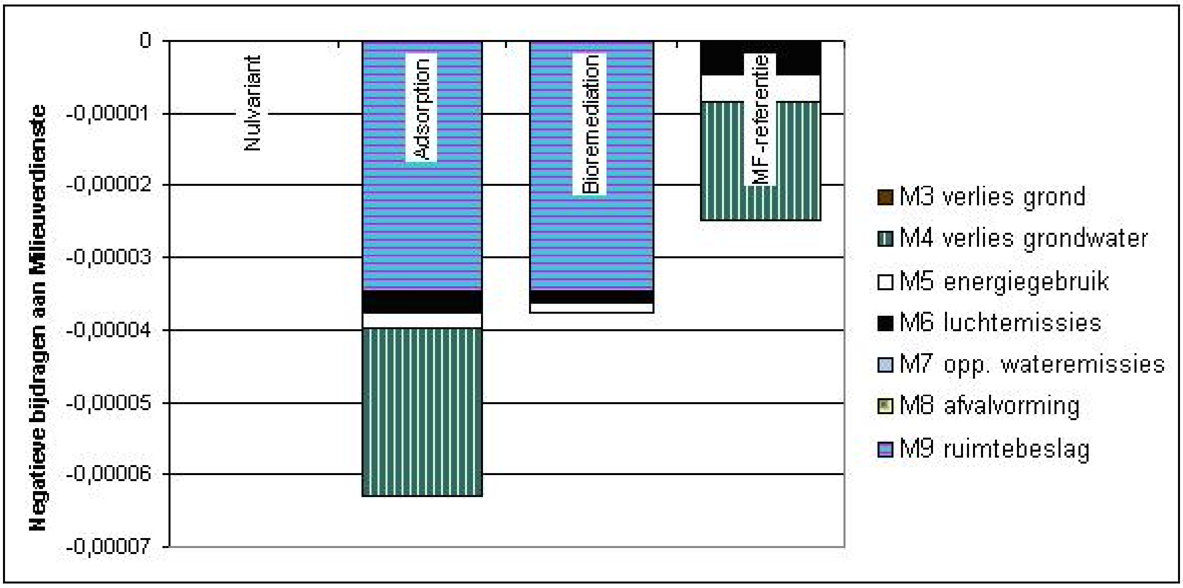

Figure 2: The results of the weighting process in the REC method. The figure shows the environmental cost for each remediation technique.

Figure 2 shows that the adsorption alternative causes more environmental costs then the bioremediation alternative. There are five categories in which the adsorption technique contributes to environmental costs. The categories are *Land use (ruimtebeslag), Waste (afvalvorming), Air emission (luchtemissies), Energy (energiegebruik)* and *Consumed groundwater (verlies grondwater).* The categories for the bioremediation technique are *Land use, Energy* and *Consumed groundwater.*

The category, which is weighted to have the most significant environmental costs, is *Land use.* The land use category, in this study, is based on the required area for the pumping and treatment equipments. The assumption that the equipments required an area of 5 m^2 was made for both techniques. The area does not seem like a big area. The reason that the land use is considers being the category, which causes the most environmental costs, could be that other data in the methods have relative low values compared to land use (see table 3).

For the adsorption technique the category that causes the second most environmental costs is *Consumed groundwater*. According to Bardos et al (2001) there is a major difference in the way in which groundwater is considered a resource. The difference is based on the supply of groundwater in a country or region. In the Netherlands the groundwater is a scare resource (van Put, 2001). This could be the reason why the consumption of groundwater is prioritised in the weighting process.

5.1.3 Interpretation

According to the results in the REC method, the adsorption technique causes higher environmental costs than the bioremediation technique. The main reason for the higher environmental costs is the fact that the groundwater is released in a ditch after treatment. In bioremediation alternative the water is infiltrated back, and therefore no groundwater is consumed. Another reason is that the adsorption technique consumes more energy. This is due to the fact that the total volume of contaminated groundwater is pumped up before treatment. A higher consumption of energy causes more emissions to the air. The adsorption technique also produces more waste.

This study presents only the results from the environmental merit perspective. To get a more comprehensive comparison of the remediation techniques the risk reduction and costs perspective should be included.

5.2 The UvA Output

5.2.1 Inventory Analysis

The output of the inventory analysis is shown in two tables. The first table illustrates the consumption of energy and materials and the second presents the transports, waste and emissions for each remediation technique. The first output is presented in table 4.

Table 4: Data of consumption of energy and materials for each remediation technique in the UvA method.

Consumption category	Unit	Adsorption	Bioremediation
Hazardous waste	kg	0,8	0,0
Activated carbon	kg	0,8	0,0
Electrical energy (total)	kWh	4,7	865,0
-Electrical energy (hydraulic pump)	kWh	4,7	1,0
-Electrical energy (treatment process)	kWh	0,0	864,0
Groundwater	m^3	216	0,0

Neither of the techniques produces much hazardous waste. The only hazardous waste is the activated carbon, which is used to clean the groundwater in the adsorption technique.

The consumption of total electrical energy is different between both remediation techniques. The bioremediation technique consumes almost 185 times more electrical energy then the adsorption technique. One reason that bioremediation consumes more electrical energy could be that the technique uses a metering pump to control the release of sodium nitrate and hydrogen peroxide into the water. The metering pump, which consumes electrical energy, is active every day during the remediation period. The hydraulic pump consumes only 1 kWh of the total electrical energy within the bioremediation technique; but with the adsorption technique, the total electrical energy is the same as the electrical energy used for the hydraulic pump.

On the basis of the output in the consumption table the conclusion is drawn that the period of time that the remediation project last has an important impact on the total electrical energy consumption for the bioremediation technique. The only thing that seems to have an impact on the metering pump is the period of time of the remediation action. How big amounts of sodium nitrate and hydrogen peroxide the pump realises do not have an impact on the electrical energy consumption. How much water and how high the water is pumped does not have a significant impact of the total energy consumption. In the adsorption technique the total consumption of electrical energy is the same as the amount of energy that the hydraulic pump consumes. The cleaning process does not consume electrical energy.

The adsorption technique consumes about 200 m^3 groundwater, which is the total volume of contaminated groundwater. The reason that the technique consumes all groundwater is that groundwater is released in a ditch after cleaning. In the bioremediation technique the groundwater is infiltrated after cleaning and therefore the technique does not consumes groundwater.

The second output of the inventory analysis is a table, which further describes the consumption of energy, transport, emission to air and water and waste. The inventory table in the UvA method consists of about 110 inventory entries. Table 5 illustrates some of the inventory entries, which have been selected from the inventory table.

Table 5: Selected inventory data from the adsorption and bioremediation technique in the UvA method. The inventory data describes the consumption of energy and the emissions to water and air caused by the remediation techniques.

Inventory entry	Unit	Adsorption	Bioremediation
Energy renewable	TJ	0,000003	0,004
Energy fossil	TJ	0,00001	0,008
Waste -total	kg	2,3	97,7
Truck transport	tkm*	0,03	2,6
Petroleum	kg	0,08	8,8
CO_2 (air emissions)	kg	6,0	692
SO_2 (air emissions)	kg	0,02	0,9
NO_x (air emissions)	kg	0,9	0,9
NO_3 (water emissions)	kg	0,00007	0,01
Al (water emission)	kg	0,006	0,3

** tkm= ton* kilometre*

The results from table 5 shows that the bioremediation technique consumes more energy, produces more waste and causes more emissions to air and water. A reason that the bioremediation causes more emissions is that the method consumes more energy.

5.2.2 Impact Assessment

In the UvA method, the output of the inventory analysis is assigned to a number of impact categories. Table 6 shows the impact categories for the adsorption technique and the bioremediation technique.

Table 6: Impact categories for each remediation technique in the UvA method.

Impact category	Unit	Adsorption	Bioremediation
Cumulative energy demand	TJ	0,0001	0,01
Waste total	kg	2,3	97,7
Waste recycling	kg	0,0	0,0
Hazardous waste	kg	0,8	0,0
Fossil resources	l/year	0,02	2,0
Water consumption	m^3	216,2	27,1
Land use	m^2year	0,2	27,4
Global warming	kg CO_2	6,8	731,4
Acidification	kg SO_2	0,03	1,6
Photo –oxidant formation	kg Ethene	0,0	0,06
Toxicity air –remote emissions	km^3	1,3	100,1
Toxicity water	km^3	0,0	0,0
Toxicity soil	ton	0,0	0,0
Odour –remote emissions	km^3	0,1	8,8
Toxicity air – near emissions	km^3	0,0	0,0
Odour – near emissions	km^3	0,0	0,0

Table 6 shows that in the most of the categories the bioremediation technique has the highest environmental impacts, most likely due to the energy use. There are five categories (*Waste recycling, toxicity to water, soil, near emissions and odour)* in which neither the adsorption technique nor the bioremediation technique causes environmental impacts. In two categories, *Water consumption* and *Hazardous waste,* the adsorption technique have the highest environmental costs.

To facilitate the interpretation of the output the results in table 6 are translated into a table with disadvantage factors. The disadvantage factors are calculated by dividing the higher value by the lower value. Table 7 presents the disadvantage factors. In the table the values for the bioremediation technique are divided by the values for the adsorption alternative. This is done for every category, except for the *Water consumption* and *Hazardous waste* category. In these categories the values in adsorption technique are divided by the values for the bioremediation technique.

Table 7: Disadvantage factors in UvA for the adsorption and bioremediation remediation techniques. The disadvantage factors are calculated by dividing the higher value for a remediation technique by the lower value for the other technique.

Impact category	Adsorption	Bioremediation
Cumulative energy demand	1	100
Waste total	1	42
Waste recycling	-	-
Hazardous waste	! *	-
Fossil resources	1	106
Water consumption	8	1
Land use	1	153
Global warming	1	109
Acidification	1	60
Photo –oxidant formation	1	79
Toxicity air –remote emissions	1	80
Toxicity water	1	54
Toxicity soil	1	112
Odour –remote emissions	1	72
Toxicity air – near emissions	-	-
Odour – near emissions	-	-

** This indicates that the bioremediation technique does not produce any hazardous waste, but the adsorption technique does. A disadvantage factors cannot be calculated, since it is not possible to divide a value by 0.*

The disadvantage factors in table 7 shows how many times a remediation technique causes more environmental costs compared to the other technique. For example, in the category *Waste total* the bioremediation technique produces 42 times more waste than the bioremediation technique. The categories marked with a “ – “ indicates that the remediation techniques do not contribute to any environmental costs.

The results in table 7 illustrates that the bioremediation technique causes between 42 and 153 times more environmental costs in some of the categories. In two categories, *Hazardous waste* and *Water consumption* the adsorption technique does contribute to more environmental costs than the bioremediation technique.

According to Volkwein et al. (1999) the disadvantage factors in many remediation cases are dependent on the diesel fuel consumption. In this study the bioremediation technique consumes 106 times more fossil fuels than the adsorption techniques (table 7). This is probably one reason for the higher disadvantage factors for the bioremediation technique within the other categories.

5.2.3 Interpretation

The results from the UvA method show that the bioremediation technique causes higher environmental costs than the adsorption technique. An important reason for the higher environmental costs is that the bioremediation consumes more energy for the treatment process. The consumption of energy causes emission to air and water and the emissions contribute to environmental problems like global warming, acidification and photo- oxidant formation. The two categories in which the adsorption technique causes more environmental costs are *Water consumption* and *Hazardous waste.* This is because the water is not infiltrated after treatment and that the activated carbon is seen as hazardous waste after being used.

The UvA method is a complement to a risk assessment. The risk assessment evaluates the risk before and after the remediation action, the spreading of toxic substances and the danger to humans and ecosystems (Volkwein et al, 1999). The results from the UvA method should therefore be compared to the results from the risk assessment, in order to get an overall picture of the remediation action. In UvA the modules are linked with a data set, and most of the data are average values (Volkwein et al., 1999). The results should therefore be seen as estimations instead of precise values.

5.3 Comparison of the Results and the Methods

The results of the methods differ in many ways. The results from the REC method shows that the adsorption technique causes higher environmental costs and the UvA method shows that bioremediation technique causes higher environmental costs. The differences in the results are dependent on many factors. In the following sections, the factors indata requirements, energy consumption, emissions, system boundaries, impact categories and weighting methods are discussed.

5.3.1 *Indata Requirements*

The REC and the UvA methods are quantitative software tools, which are designed to support decision makers. According to Bardos et al. (2001) the advantages with using a software tool are that calculations can easily be done and that it is possible to get a rapid evaluation of the effects by changing data. Some of the limitations of quantitative methods are that it is not possible to make calculations for less noticeable effects, such as landscape degradation. Another concern is the costs of the work for finding all necessary indata in the method (Bardos et al, 2000).

In the present study an examination of the differences in indata between the methods was made. Finding available indata for the UvA and REC methods were not considered as a problem. The reports about the case study were based on basic investigations on the site, and contained most of the necessary data. This indicates that if the results from investigations of the site are gather properly, it is possible to find the required indata for the REC and UvA methods. There are however some variables in the UvA method where it can be difficult to find available data in reports about the site. Examples of variables are *Average density of the soil* and *Concentration capacity of activated carbon*. If it is hard to find data in these categories the method gives examples of average data that can be used instead.

Most of the indata variables are the same for both methods. Examples of these variables are *Volume of groundwater, Land use* and *Lifting height.* In UvA and REC the same data were used in these variables, and therefore the differences in results between the methods were not due to these variables. There is however some indata variables that are included in the UvA method, but are not considered in the REC method. These variables are for example *Concentration capacity of activated carbon* and the use of *Sodium nitrate* and *Hydrogen peroxide.* These variables are included when the environmental impacts caused by the additives are calculated. How the additives are calculated in the methods is further described in section 5.3.4.

The main findings that appeared when the indata requirements are investigated is that it is possible to find available indata for the UvA and REC methods, as long as the results from the investigations on the site are collected in reports. The main difference in indata requirements between the methods is that the UvA method considers more indata about the additives.

5.3.2 Energy Consumption

The energy consumption for the remediation techniques is different between the methods. Since the use of energy affects many of the impact categories, the difference in results between the methods is largely due to the different in how energy consumption is calculated. Table 8 shows the difference in consumption of energy between the techniques and the methods.

Table 8: The consumption of energy for the remediation techniques within the REC and UvA method.

Remediation technique	Total energy (kWh)	Pump (kWh)	Treatment (kWh)
Adsorption in REC	39	17	22
Adsorption in UvA	4,7	4,7	0
Bioremediation in REC	26	4	22
Bioremediation UvA	865	1	864

The output of the REC method shows that the adsorptions technique consumes more energy and the UvA method shows that the bioremediation method consumes more energy (table 8). The reason for the difference is that the methods calculate the consumption of energy in different ways, which will further be explained bellow.

There are two main processes, which consume energy in a remediation process. The first process is when pumping up the groundwater and the second step is the treatment process. For both methods the adsorption technique consumes more energy than the bioremediation technique when pumping up the groundwater. This is due to the fact that all groundwater is pumped up in the adsorption technique. In the bioremediation technique only 50 m^3 of the groundwater is pumped up. Table 8 illustrates that the values for the energy consumption differ between the methods for the adsorption technique in the pumping process. A reason for the different values is that the methods are linked to different data sets. Both data sets are based on average data, but the data sets could vary in for example the region the data are adjusted to and the age of the data. In the UvA method most of the data are adjusted to the conditions in Western Europe and the data are mainly from 1988 to 1996 (Volkwein et al, 1999). If the data were not so old and if it were adjusted to the condition in Germany the results might look different.

The consumption of energy for the treatment process is very different between the methods. In the REC method the bioremediation technique consumes 22 kWh while according to the UvA method the technique consumes 864 kWh. The methods consider different factors when calculating the energy consumption for the bioremediation technique. In the REC method the energy consumption is only dependent on the volume of groundwater to treat. The consumption is not dependent on the remediation technique that is used and therefore the adsorption and the bioremediation technique have the same consumption of energy in the treatment process. In the UvA method the treatment process is dependent on the technique. The energy consumption is also dependent on the kind and amount of additives that is used (see section 5.3.4) and how many days the groundwater is treated. In the module, which is used in the UvA, method for the bioremediation technique is called *Mikrobiologische-grundwasserreinigung in situ.* In this module an assumption that the remediation technique uses a metering pump for the additives are made. The metering pump consumes energy every day during the remediation action, and this is one reason for the extensive energy consumption.

5.3.3 Emissions

The emission to water and air are mainly dependent on the consumption of energy. In the REC method the adsorption technique consumes more energy and therefore causes more emissions than the bioremediation technique. In the UvA method the bioremediation technique consumes more energy and causes more emissions.

The methods include different kinds of emissions. The REC method only considers three types of emission. The emissions are CO_2, NO_X and SO_2, and are entirely due to the use of energy (Drunen et al., 2000). These emissions are then classified in the categories *Water emissions* and *Air emissions.* In these categories the emissions are calculated to one value, therefore it is not possible to study for example how much more CO_2 that is caused by an adsorption technique compared to the bioremediation technique. It is only possible to study how much more air emissions the adsorption technique causes.

The UvA method gives a more extensive picture of the emissions to air water and soil than the REC method. The inventory table in the UvA method for the adsorption and bioremediation technique shows about 80 different emissions. Some of these emissions are illustrated in table 5. The emissions in the inventory analysis are then classified and characterized to a number of impact categories. When the impact category *toxicity* is calculated 60 different emissions are included and in the impact category *odour* eight emissions are included (Volkwein et al., 1999). In the UvA it is possible to study how much more CO_2 the bioremediation technique causes compared to the adsorption technique. It also possible to study how many more times the bioremediation technique contribute to the global warming compare to the other technique.

5.3.4 System Boundaries

The LCA methods used in this study are simplified models of a remediation action. The methods are designed with different system boundaries and the system boundaries might have an impact of the results (Gustafsson et al., 1982). In this section the differences between the methods in system boundaries to additives and production machineries are discussed.

In the UvA method the environmental impacts caused by production of additives, like activated carbon and electron acceptors are included (Bender et al., 1998). Bender et al. (1998) used the UvA method to study different remediation techniques on a contaminated site. The outputs from the study show that the kind of additives that is used has a significant impact of the results. Bender et al used either nitrate or hydrogen peroxide as an electron acceptor for the bioremediation technique. The results from the UvA method showed that the bioremediation technique has low environmental costs if nitrate was used and if hydrogen peroxide was used, the technique shows higher environmental costs. The reason for the higher environmental costs when hydrogen peroxide is used is because the production of hydrogen peroxide is an energy consuming process (Bender et al., 1998).

In the REC method the production of additives are not included (Drunen et al., 2000). For example the production of hydrogen peroxide and activated carbon are not included in the results. Since the additives have an impact on the results, the results probably would look different if the additives were included in the REC method.

Neither the UvA method nor the REC method deals with data of specific machineries and services (Bender et al., 1999). Example of specific data is the age and state of the machineries and the manufacturer of the machineries. The reason why the methods use average data instead of specific data are because the designers of the method think there are problems in finding available data of the machineries (Volkwein et al 1999).

5.3.5 Impact Categories

The first step in the impact assessment is to classify the inventory data to a number of impact categories (Finnveden, 1996). The impact categories in which the REC and the UvA method classify the inventory data are illustrated in table 9.

Table 9: The categories in which the UvA and the REC methods classify inventory data. (Volkwein et al, 1999; IVM, 2003)

Impact category	UvA	REC
Energy	X	X
Water	X	X
Land use	X	X
Waste	X	X
Global warming	X	
Acidification	X	
Photo-oxidant formation	X	
Toxicity	X	
Odour	X	
Noise	X	
Soil quality		X
Groundwater quality		X
Consumed Soil		X
Air emission		X
Water emission		X

Table 9 shows the difference in impact categories between the methods. According to Zetterberg and Finnveden (1997) the impacts categories have an important impact on the results. In the UvA method the data is classified in ten main categories and the REC method has nine impacts categories. Four impact categories (energy, water, land use and waste) are the same for the methods. It is important to keep in mind that even if the categories are the same, the underlying calculations in the categories, may be different between the methods.

The emissions, which are caused by the remediation action, are classified in two categories in the REC method. The categories are *Air emission* and *Water emission* The UvA method classifies the emissions in five categories (global warming, acidification, photo-oxidant formation, toxicity and odour). There are differences in the way the methods classify the emissions. In the REC methods the categories are related to the medium the emissions are released in and the categories in the UvA method are related to the environmental problems the emissions cause.

Two impact category tables were used to study the difference in environmental problems between the UvA method and other tables. The tables are found in Nordic Guidelines (Zetterberg and Finnveden, 1997) and in Ribbenhed et al. (2002). The latter studied a remediation action. The results from the comparison shows that the Nordic Guidelines includes the same four environmental problems as the UvA method, but the Nordic Guidelines also includes *eutrophication* and *ozone-layer depletion*. Ribbenhed et al. (2002) uses the same environmental problems as the UvA method, but the method also includes *eutrophication*. Eutrophication is a serious environmental problem, which causes changes and damages to ecosystems (Warfvinge, 1997). In order to receive a more comprehensive picture of the environmental problem caused by a remediation action eutrophication and depletion of the ozone layer should be included.

Two other dissimilarities between the methods are the way local and positive environmental impacts are considered. In the UvA method there are three categories (toxicity, noise, odour), which addresses to the people living on or in the neighbourhood of the contaminated site (Volkwein et al., 1999). In the REC method the local impact are included in the Risk reduction perspective instead (Drunen et al., 2000), which was not included in the present study. The REC method includes two categories, which consider the positive environmental impacts of a remediation action. The categories are *Soil quality* and *Groundwater quality.* The UvA method does not have similar categories.

5.3.6 Weighting Methods

The aim of a weighting method is to present the relative importance of the impact categories. Several methods for weighting have been developed and the methods facilitate the interpretation of the results. A weighing method is a subjective process and it has been shown that different methods give different results (Finnveden, 1996). In the REC method the weighting process is based on a panel of experts (IVM, 2003). The result of the weighting process in REC is presented in a figure (figure 2). In the figure it is easy to interpret which impact categories that according to panels of expert, cause the most important environmental costs. If another weighting method were used in the REC method, the results would look different. Another factor, which may have an impact of the outputs, are the formulations and understanding of the questions that the people in the expert panel should answer (Finnveden, 1996). The competence of the people in the expert panel could also have an impact of the results. Zetterberg and Finnveden (1997) present a study where an expert panel were used. The people in the expert panel were for example representatives from the industry, authorities and Non Governmental Organisations. In the REC method the people in the panel are experts in environmental science and soil science (Drunen et al., 2000). It is possible that the people in the REC method have a more limited approach then if people from different parts of the society were included in the panel.

The UvA method does not include a weighting method. The results are presented in a table with disadvantage factors and the user of the method will make the interpretation of the relative importance of the impact categories (table 6). In the table it is possible to make a comparison of the remediation techniques, but not of the impacts categories. Since the method does not include a weighting process there is no subjective weighting moment in the method. The user of the method makes the subjective interpretation and therefore the interpretation is dependent of the competence and knowledge of the user.

5.4 REC and UvA as Tools for Sustainable Development

Any sustainable approach must consider the economical, environmental and social aspects of a project. Remediation of contaminated sites ideally should be sustainable. For example, the remediation action should not lead to unacceptable environmental costs and the action should not causes social and economical concerns (Bardos et al., 2000).

An LCA often considers the wider environmental impacts of a remediation action, but according to Shakweer and Nathanail (2003) there is a need for methods, which also consider the social and economical aspects of sustainable development. Therefore the *AfrS* method was developed by Shakweer and Nathanail (2003). The AfrS method has an LCA approach and the output of the method illustrates the remediation techniques from an environmental, economic and social point of view. The social component is integrated in the method by asking stakeholders' representatives to weight different environmental factors. The economic component is included by dividing the environmental impact saved by carrying out the remediation by the total costs of the remediation (Shakweer and Nathanail, 2003). Also other methods exist which attempt to include the social aspects in the decision of a remediation technique (Suèr and Nilsson-Påledal, 2003).

In the REC and UvA methods the environmental component of sustainable development is included. The REC method also includes the economic perspective, but the UvA and the AfrS methods do not calculate the economic component in the same way. Neither the REC method nor the Uva method considers the social component. In the context of sustainable development the consideration of the environmental and economic perspectives are not sufficient to be able to meet the need for future generations. The social aspect should therefore also be included. The social aspects can for example be included by arranging meetings for the stakeholders. In the meetings the problems, objectives and solutions should be explained and the stakeholders could thereafter be involved in evaluating the importance of different environmental problems. The evaluation is then considered in the weighting process (Shakweer and Nathanail, 2003).

6 CONCLUSION

The results from present study show that the REC and UvA methods give different indication of which remediation technique that causes the most environmental costs. The REC method shows that the adsorption technique causes the most environmental costs, and UvA shows that the bioremediation causes has the highest environmental impact. The main reasons for the higher costs for the adsorption technique in the REC method are that the technique consumes more groundwater, energy and hazardous waste. Since the technique consumes more energy it also causes the most emissions. The impact category, that after the weighting process, considered being the category that causes the most environmental cost for both technique was *Land use*. A reason for the high impact in *Land use* has could be that other data in the methods have relative low values compared to this category.

In the UvA method bioremediation is the technique that consumes more energy than the adsorption technique. The main reason to the extensive energy consumption is that the bioremediation technique consumes more energy in the treatment process. This is because the technique uses a metering pump, which is active every day during the remediation action. The bioremediation technique also causes more emissions and this is due to the use of energy. The results from the inventory analysis in the UvA method are assigned to ten main impact categories. In most of the impact categories the bioremediation technique causes more environmental impact, but for the two categories, *Consumed groundwater* and *Hazardous waste* where the adsorption technique causes higher costs.

The difference in the results between the methods is mainly due to the fact that the methods use different system boundaries, different ways to consider additives and different ways of calculating the consumption of energy. The difference in results is not in great extent dependent on the indata requirements since most of the categories are the same for both methods.

In REC, the consumption of energy mainly is dependent of the volume of groundwater that is pumped up and treated. In the UvA method the consumption of energy also is dependent on the volume of groundwater, but the method also considers which treatment technique is used. Another difference between the methods in how they calculated energy consumption is in how additives are considered. The production of additives is not included in the REC method, but it is included in the UvA method. Since the production of for example hydrogen peroxide is an energy consuming process the REC method exclude a factor that could have a significant impact of the consumption of energy. In the present study the consumption of energy was very different between the methods. Since the use of energy affects many of the impact categories, the difference in results between the methods is in great extent due to the different in how energy consumption is calculated.

The REC method considers three kinds of emissions. In UvA about 60 different emissions are included. The emissions and the other outcome of the inventory analysis are assigned to a number of impact categories. The REC method classified the emission in two categories, which are related to the media that the emissions are released in (air and water). The REC method classified the emission to the environmental problem that they cause. Other differences are that the REC method includes two positive categories and UvA includes local environmental impact.

The REC and UvA methods are tools, which are designed to help decision makers to study which remediation technique that causes the least environmental costs. In this thesis the methods give different indication of which technique that causes the most environmental costs. There are however not a method that are “ better” than the other, they only considers different factors and have different system boundaries. The UvA method has a more wider approach. The method includes for example the production of additive and it considers more emissions and environmental problems. REC does not require as much indata as Uva and the production of additives are not included.

A conclusion in this study is that a decision process of which remediation technique to use at a contaminated site could be dependent on which method is used as a decision support tool. Before a decision of which remediation technique to use the decision maker should investigate the underlying assumptions, calculations and system boundaries in the method. The decision maker should investigate this in order to be able to consider these factors when the results from the methods are interpreted.

7 REFERENCES

7.1 Publications

Asante-Duah K. (1996) *Management of contaminated site problems,* CRC Press/Lewis Publishers, London, Great Britain

Bardos R. P., Kearney T. E., Nathanail C. P., Weenk A., Martin I. D. (2000) Assessing a Wider Value of Remediating Land Contamination, *ConSoil 200 7th International FZK/TNO Conference on Contaminated Soil*, Leipzig, Germany.

Bardos R. P., Mariotti C., Marot F., Sullivan T. (2001) Framework for Decision Support used in Contaminated Land Management in Europe and North America, *Land Contamination & Remediation 9(1),* 149-162.

Bedient P., Rifal S., Newell C. (1999) *Ground water contamination, Transport and remediation,* Second edition, Prentice Hall, London, Great Britain

Bender A., Volkwein S., Battermann G., Hurtig H-W., Klöpffer W., Kohler W. (1998) Life Cycle Assessment for Remedial Action Techniques: Methodology and Application, *Contaminated Soil,* 367-376

C.A.U. GmbH (1998) Umweltbilanz von Altlastensanierungsverfahren, Version 1.03, Germany

CLARINET (2002) *Review of Decision Support Tools for Contaminated Land Management and their Use in Europe,* Austria Federal Environmental Agency, Austria

Drunen van M.A., Beinat E, Nijboer M.H., Hasselhoff A., Veld in 't M., Schütte A.R. (2000) *De RMK-methodiek voor het beoordelen van bodemsaneringsvarianten - een methode gebaseerd of Risicoreductie, Milieuverdienste en Kosten - RMK fase 3,* Tauw Milieu, R1111111/ATH/D01 internetversie 12 April 2000. Translation of selected parts from Dutch by Pascal Suèr

Finnveden G. (1996) *Valuation Methods within the Framework of Life Cycle Assessment,* IVL Report B1231, IVL Publikationsservice, Stockholm, Sweden

Finnveden G. (1998) *On the possibilities of Life Cycle Assessment, Development of methodology and review of case studies,* Doctoral thesis, Natural Resources Management, Department of Systems Ecology, Stockholm, Sweden

Gustafsson L., Lanshammar H., Sandblad B (1982) *System och modell, En introduktion till systemanalysen,* Studentlitteratur, Lund, Sweden

Larsson L., Lind B. (2001) *Biologiska metoder för in-situ sanering av organiska markföroreningar, en kunskapssammanställning, "State of the art",* SGI Varia 499, Sweden

Lindahl M., Rydh C-J., and Tingström J. (2000) *En liten lärobok om Livscykelanalys,* Högskolans reproservice, Kalmar, Sweden

Ribbenhed M., Wolf-Watz C., Almemark M., Palm A. and Sternbeck J. (2002) *Livscykelanalys av marksaneringstekniker för förorenad jord och sediment,* Report B1476, IVL Publikationsservice, Stockholm, Sweden

Ryding S-O., Ekvall T., Karlsson L., Karlsson R., Nevén C-O., Tillman A-M., Steen B., Westerlund G., Karlsson L., Arvidsson P., Troberg H., Mälhammar G., Sund L., Swan G., Almgren R. (1998) *Miljöanpassad produktutveckling*, Industriförbundet, Stockholm, Sweden

Nobis, RMK Software for Windows, the Netherlands

ScanRail Consult, HOH Water Technology, NIRAS and Revisorsamvirket (2000a) *Environmental/Economic Evaluation and Optimising of Contaminated Sites Remediation-, Executive Summary,* EU LIFE project no. 96ENV/DK/0016, Copenhagen, Denmark

ScanRail Consult, HOH Water Technology, NIRAS and Revisorsamvirket (2000b) *Environmental/Economic Evaluation and Optimising of Contaminated Sites Remediation-Methods to Involve Environmental Assessment,* EU LIFE project no. 96ENV/DK/0016, Copenhagen, Denmark

SGI (2000) *Blackstad klockaregård 1:0 Blackstad gata 13, Blackstad Västerviks kommun; Miljöteknisk markundersökning vid nedlagd bensinstation.*

SGI (2002) *Blackstad Klockaregård 1:10 Ekhyddan, Blackstad Västerviks kommun; Rapport In situbehandling av petroleumförorenat grundvatten.*

Shakweer A. F., and Nathanail P. C. (2003) LCA Methodology for Remediation Strategy Selection, *ConSoil 2003 8th International FZK/TNO Conference on Contaminated Soil*, Gent, Belgium, Submitted

Suèr P. and Nilsson-Påledal J. (2003) Life cycle thinking for soil remediation- a literature review, *J Soil Sediment Contam*, Submitted

Swedish Environmental Protection Agency (2003) *Lägesrapport för efterbehandlingsverksamheten år 2002,* Stockholm, Sweden.

Swedish Environmental Protection Agency (1999) *Metodik för inventering av förorenade områden –bedömningsgrunder för miljökvalitet; vägledning för insamling av underlagsdata*, Report 4918, Almqvist & Wiksell, Uppsala, Sweden

Swedish Environmental Protection Agency (1998) *Förslag till riktvärden för förorenade bensinstationer,* Report 4889, Naturvårdsverkets förlag, Stockholm, Sweden

Van Put (2001) *Some administrative, policy and juridical aspects in relation to groundwater protection in the Netherlands,* Workshop on the protection of groundwater used as a source of drinking water supply, Budapest, Hungary

Volkwein S., Hurtig H-W., Klöpffer W. (1999) Life Cycle Assessment of Contaminated Sites Remediation, *Int. Journal LCA 4,* 263-274.

Warfvinge P. (1997) *Miljökemi, miljövetenskap i biogeokemiskt perspektiv,* KFS, Lund, Sweden

Zetterberg L., Finnveden G. (1997) *Värderingsmetoder för bedömning av den total miljöpåverkan från produkter och tjänster,* IVL Report B1262, IVL Publikationsservice, Stockholm, Sweden

7.2 Internet

IVM, Institute for Environmental Studies, Vrije University, the Netherlands, http://130.37.129.100/english/o_o/instituten/IVM/research/rmk/rec.htm, Accessed at 2003-02-08

7.3 Personal Communication

Larsson Lennart, Swedish Geotechnical Institute, 2003-04-04
Suèr Pascal, Swedish Geotechnical Institute, 2003-03-14