Economic comparison of remediation methods for hydrocarbon contaminated areas

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BSc. Franz Strasser

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Contents

List of figures

List of tables

List of abbreviations

Diss.	Dissertation
f.	following page
ff.	following pages
Ed.	Editor
ed.	edited
w.a.s.	without author statement
s.	see
p.	page
et al.	et alteri or et alii = and others
Cf.	Confine = compare
qt.	quoted by
BTEX	Benzol, Toluol, Ethylbenzol and Xylol
CBA	Costs Benefit Analysis
DNAPL	Dense Non-aqueous Phase Separated Liquid, an immiscible organic phase with a relative density > 1
EA	Environmental Agency
EIA	Environmental Impact Assessment
EPA	Environmental Protection Agency
DST	Decision support tools
HC	Hydrocarbons
LCA	Life Cycle Analysis
LNAPL	Light Non-aqueous Phase Separated Liquid, an immiscible organic phase with a relative density < 1
MCA	Multi Criteria Analysis
MNA	Monitored Natural Attenuation
NAPL	Non-aqueous Phase Liquid
NPV	Net Present Value
P&T	Pump and treat
PRB	Permeable reactive barrier
PCB	Polychlorinated biphenyls
PAH	Polycyclic aromatic hydrocarbon
SPR	Source Pathway Receptor
SVE	Soil vapour extraction
SVOC	Semi Volatile Organic Compounds
VOC	Volatile Organic Compounds
WFD	Water Framework Directive
WHO	World Health Organisation

1 Zusammenfassung

Der Austritt von Kohlenwasserstoffen und die nachfolgende Kontamination des Untergrundes können z.B. während der Exploration, der Lagerung, dem Transport oder bei Unfällen sowie Rohrbrüchen vorkommen. Dadurch kann es zu weitreichenden Kontaminationen des Untergrundes kommen. Sobald ein kontaminiertes Grundstück gefunden wurde, ist die erste Frage die auftritt, welche Dekontaminationsmethode am besten für die Dekontamination geeignet ist. Diese Frage kann, je nach den gegebenen Umständen, entweder sehr einfach oder aber sehr schwierig zu beantworten sein. Diese Arbeit kann als Orientierungshilfe für Wissenschaftler, die sich mit kontaminierten Grundstücken auseinandersetzen, gesehen werden. Zuerst beschäftigt sich die Arbeit mit der Beschaffenheit des Untergrundes. Grundsätzlich kann man den Untergrund in eine gesättigte und eine ungesättigte Zone einteilen. Die Unterscheidung der beiden Zonen ist wichtig weil man auch die Dekontaminationsmethoden danach einteilen kann ob sie entweder die gesättigte, die ungesättigte oder beide Zonen erfolgreich dekontaminieren können. Das zweite Kapitel bietet einen Überblick über die gängigsten Dekontaminationsmethoden. Dabei werden technische Beschreibungen der unterschiedlichen Methoden geliefert beziehungsweise Bedingungen unter welchen die untersuchten Methoden grundsätzlich einsetzbar sind. In diesem Kapitel werden auch die Kosten und die wichtigsten Einflussfaktoren der Kosten, für die untersuchten Methoden, untersucht. Wenn einmal einige Dekontaminationsmethoden, für ein kontaminiertes Grundstück, als grundsätzlich geeignet eingeschätzt werden dann gibt es wichtige Faktoren die es für die Suche nach der geeigneten Methode zu beachten gibt. Diese Faktoren, z.B. Risiko Management, Nachhaltige Entwicklung, Technische Eignung, Kosten und Nutzen und Stakeholder werden genauestens im dritten Kapitel untersucht. Desweiteren wird in diesem Kapitel ein System vorgestellt mit dessen Hilfe man die optimale Dekontaminationsmethode für ein kontaminiertes Grundstück finden kann. Das vierte Kapitel beschäftigt sich mit gesetzlichen Bestimmungen die es bei der Durchführung von Dekontaminationen zu beachten gilt, sowohl in Europa als auch in Österreich. Das letzte Kapitel der Arbeit beschäftigt sich mit dem wirtschaftlichen Vergleich von Dekontaminationsmethoden. Der Vergleich wurde mit Daten der OMV durchgeführt. Daten über die Kosten von neun insitu Projekten, welche zurzeit von der OMV durchgeführt werden, und Daten welche für die Berechnung der Aushubkosten notwendig sind wurden zur Verfügung gestellt. Das Hauptaugenmerk des wirtschaftlichen Vergleichs liegt auf dem Vergleich der Aushubkosten mit den Kosten die für eine insitu Methode anfallen. Für diesen Zweck wurde ein Program entwickelt das die Aushubkosten berechnen kann, solange bestimmte Input Parameter gegeben sind. Das Program wurde in Excel geschrieben und es wurde mit dem Software Tool @risk verknüpft. Mit Hilfe dieser Verknüpfung war es möglich die minimalen, die wahrscheinlichsten und die die maximalen Aushubkosten mit einer bestimmten Wahrscheinlichkeit, für die neun untersuchten Projekte, zu berechnen. Zusätzlich zu dem wirtschaftlichen Vergleich wurden, die Hauptkostenverursacher für die untersuchten Methoden untersucht. Es wurde auch berechnet ab welchem kontaminierten Volumen die untersuchten insitu Methoden, von einem ökonomischen Standpunkt aus betrachtet, dem Aushub vorzuziehen sind.

2 Introduction

The discharge of HC, and subsequently subsurface contaminations, may occur during oil exploration, storage and distribution of HC or via accidents such as pipe bursts. A wide-ranging spread of the contamination, from its origin, may occur as a result of HC flowing into porous media. Once a contaminated site has been identified, the first question that usually arises is what remediation method should be implemented for the remediation of the contaminated site. The choice of the optimal remediation method can be, depending on the site specific circumstances, either straight forward or quite a complex and challenging process. This thesis can be seen as guidance for a contaminated land manager, providing important underlying information for answering the above question. The thesis first outlines the characterisation of the subsurface. Generally, the subsurface can be divided in an unsaturated zone and in a saturated zone. The dividing into such zones is of importance because remediation methods can be divided according to their capability of remediating the saturated, the unsaturated or both zones. The second chapter therefore provides an overview of the most prevalent remediation methods according to their capability of remediating those zones. Technical descriptions of the investigated remediation methods are discussed, as well as the general applicability with respect to the limitations under which such remediation methods would be suitable for contaminated sites. This chapter also assesses costs of the investigated remediation methods and their most important cost influencing factors. Once a few remediation methods have been identified as technically and generally viable for the remediation of a contaminated site, other important factors which influence the decision making process come into play. These factors, e.g. risk management, sustainable development, technical feasibility and suitability, costs and benefits and stakeholder satisfaction, are explained in detail in the third chapter. In addition, a framework for the assessment of suitable remediation methods for a contaminated site is set out in this chapter. The fourth chapter deals with the legislation associated with contaminated land in Europe and in Austria. Generally, it can be said that the legislation in Europe concerning the treatment of contaminated sites is quite complex and there are significant differences in European countries' legislations. The Heracles Study gives an overview over the most important differences concerning soil screening and groundwater screening values in fifteen European countries. It also provides information on the main sources from which the screening values where originally derived. A description of the most important laws concerning handling of contaminated sites in Austria is also provided. The last part of the thesis covers an economic comparison of the remediation methods. The economic comparison is carried out with data which was provided by OMV. The cost data of nine insitu projects (which are currently carried out by OMV) and cost data which is necessary for the calculation of the excavation costs was provided by OMV. The main focus of the economic comparison lies on the cost comparison of insitu methods compared to excavation. For this purpose a program was developed which simulates the excavation costs if associated input parameters, such as the spatial extent of the contamination or cost input parameters are known. The program which was written in excel was expanded with a software tool (@risk). With the help of @risk (which is based on the concept of Monte Carlo Simulation) it was possible to calculate the minimum, most likely and maximum excavation cost with a certain probability, for the investigated projects. In addition to the economic comparison, the main cost causers for the investigated remediation methods are investigated and a boarder is calculated under which insitu methods are strictly, from an economic point of view, preferable over excavation.

3 Contaminants in the subsurface

In the following a short summary is provided on the issues which are subsequently being investigated in this chapter. Before any judgment can be made which remediation methods might be viable for remediating a site successfully, the subsurface needs to be investigated. Understanding the build-up of the subsurface and groundwater flow is absolutely essentially in order to be able to predict the spread of the contaminants in the subsurface. Especially, the movement of contaminants as a separate phase, soluble transport of the contaminants in the groundwater and the processes which determine the soluble transport such as advection, diffusion, dispersion are the main factors which are responsible for the spread of the contaminants. Generally it can be noted, that contaminants can be present in four different phases (aqueous, gaseous, immiscible or solid) within the subsurface. The particular circumstances under which a mass transfer of contaminants (from one to another phase) and the associated conditions under which this happens are of great importance for the choice of an appropriate remediation method for a contaminated site.

3.1 Description of the subsurface

The geological material in the subsurface persists of porous media that contains interconnected voids and within those voids liquids are able to flow. The subsurface consists of an unsaturated zone which is also known as the vadose zone, a saturated zone and a capillary fringe whereby the capillary fringe is part of the saturated zone. The top of the capillary fringe forms the boundary between the saturated and the unsaturated zone. The capillary fringe exists because of surface tensions within the voids of the saturated zone which draw the groundwater upwards from the saturated zone into the capillary fringe. The pores of the unsaturated zone contain liquids and air whereas the interconnected pores of the saturated zone just contain liquids. A saturated zone that offers enough groundwater that could be used for irrigation is called an aquifer. Beneath the aquifer there is often an impermeable layer such as clay or some kind of bedrock.[1]

The next figure gives a graphical illustration of the above mentioned description.

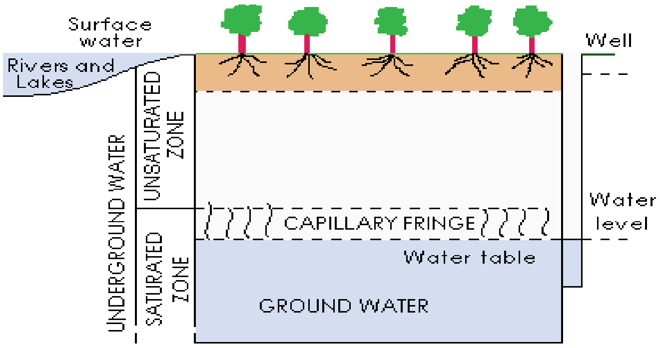

Figure 1: Graphical description of the subsurface[2]

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[1] Cf. BHANDARI A. et al. (2007), p. 5

[2] Source: URL: http://www.purdue.edu

3.2 Groundwater flow and solute transport

The groundwater flows through the interconnected pores within the saturated zone. The interconnected pores represent the effective porosity of the subsurface material. The most important criteria that govern the movement of the groundwater under a hydraulic gradient are the interconnectivity of the pores and the pore size distribution. Those criteria are responsible for the effective porosity of the subsurface material and consequently the amount of groundwater that is able to flow. The hydraulic gradient describes the change in groundwater head over a given distance and is the driving force for the groundwater flow in the saturated zone. The groundwater flow velocities can be described by a laminar flow regime and depending on the site specific circumstances they can range from centimetres to tens of meters per day. Groundwater flow can be described by Darcy's law, which states that the velocity of groundwater is directly proportional to the hydraulic gradient.[3]

For a saturated porous medium and coordinated directions aligned with the principal axis of the conductivity tensor, Darcy's law for a particular coordinate axis can be expressed in terms of flow rate as:[4]

$$Q = qA = -KA\frac{dh}{dx}$$

where:

Q = Volumetric flow

Q = volumetric flux (L/T)

A = area normal to flow (L^2)

K = hydraulic conductivity (L/T)

h = hydraulic head (L)

x = distance in flow direction (L)

The hydraulic conductivity represents the rate at which water flows through a cross sectional area of a permeable medium under the influence of a hydraulic gradient; it depends primarily on the rock type, the fluid viscosity and the density. The next figure summarises typical values of permeability and horizontal hydraulic conductivity for common subsurface materials. The transport of contaminants in an aquifer happens either under normal hydraulic gradients or under gradients that are created by injection wells during the remediation of a contaminated site. The transport of dissolved contaminants in the saturated zone

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[3] Cf. BHANDARI A. et al. (2007), p. 6

[4] Ct. FLACH G. (2004), p.22

can be described as the result of the combined action of advection, diffusion and dispersion processes.[5]

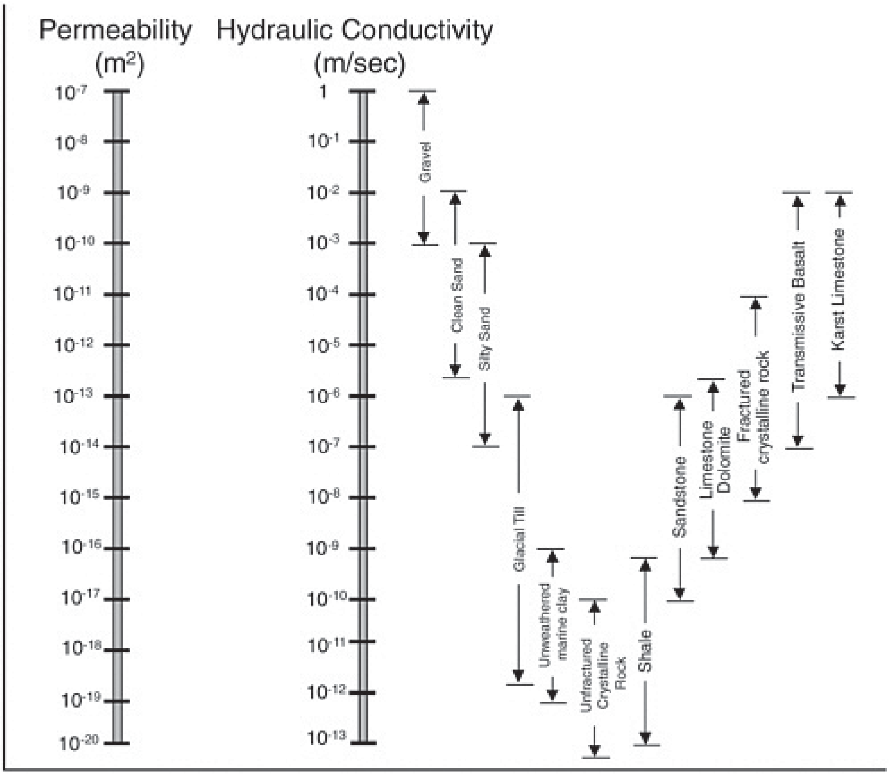

Figure 2: Permeability and hydraulic conductivity for common subsurface material[6]

Understanding the transport of the dissolved contaminants is vitally for a contaminated land manager in order to get a good approximation of the magnitude of the contamination plume in the subsurface.

Advection

When dissolved contaminants travel with the same speed as the average velocity of the groundwater this is termed advective transport.[7]

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[5] Cf. BHANDARI A. et al. (2007), p. 8

[6] Source: Water Technology Subsurface Board (2004), p.38

[7] Cf. Geophysics study committee (1984), p. 38

The rate of advection is usually described by the following equation:[8]

$$v = \frac{Ki}{n}$$

where:

v = average velocity of water movement (m/d)

K =hydraulic conductivity (m/d)

i = hydraulic gradient

n = transport velocity

Dispersion and diffusion

Usually, the dissolved contaminants within the groundwater are moving at rates that differ from the average groundwater velocity. Some move faster and some move slower than the average groundwater velocity, this phenomenon is called dispersion and is caused by a number of factors.

A short explanation of the most important factors that are responsible for dispersion is provided in the following:[9]

1. The contaminants tend to spread from highly concentrated areas to areas of less concentration, this process is called diffusion.
2. When the fluids move through the pores they move faster through the centre of the pores than along the edges because of friction.
3. The fluids also will tend to move faster through the larger pores than through the smaller pores.
4. The molecules of the contaminants follow different flow paths meaning that some molecules travel longer flow parts than others.

Dispersion of contaminants is usually described by the following equation:[10]

$$D_h = D \times T + \alpha \times v$$

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[8] Ct. MCMAHON A. et al (2001), p.26 f.

[9] Cf. ZHANG P., p.16.2

[10] Ct. MCMAHON A. et al (2001), p.29

where:

D_h= the coefficient of hydrodynamic dispersion (m^2/s)

D = the diffusion coefficient

T = dimensionless coefficient related to tortuosity

α = the dispersivity of the medium (m)

v = velocity (m/s)

3.3 Mechanisms which govern the subsurface flow of contaminants

Generally, subsurface contamination can occur in four phases. In the *gaseous phase* the contaminants are present as vapours in the unsaturated zone. In the *solid phase* the contaminants can be adsorbed on the soil particles either within the unsaturated and the saturated zone. In the *aqueous phase* the soluble contaminants are dissolved into the pore water in the unsaturated zone and the saturated zone. Hydrophobic contaminants can also exist in the *immiscible phase* as non-aqueous phase liquids which do not mix with the groundwater.[11]

The subsurface movement of contaminants is primarily driven through three mechanisms:

- Dissolution into water, which occurs within the unsaturated and the saturated zone
- Volatilisation of the volatile contaminants which occurs in the unsaturated pore spaces
- Migration of the contaminants as a Non-aqueous Phase Liquid (NAPL)

3.3.1 Dissolution

The dissolution of contaminants into the aqueous phase can occur from gases such as carbon dioxide, hydrogen sulphide or methane which are produced within the saturated zone or from gasoline components that are found within the unsaturated zone. Other potential sources of dissolution include precipitated solids, geological deposits, bulk liquids, residual contamination in the unsaturated zone or NAPL in the saturated zone. [12]

The air water partitioning of solutes is described by Henry's law. It states that the concentration of a solute gas in solution is directly proportional to its partial pressure above the solution.

$$C_e = K_h \times p$$

where:

C_e = the aqueous phase solute concentration at equilibrium with a gas with a partial pressure of the solute

K_h = the temperature dependent Henry's law constant

p = the partial pressure of the solute

In this context, the homepage www.henrys-law.org is to mention. It provides a large range of Henry's law constants for various solutes.

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[11] Cf. GENSKE D. (2003), p.20 f.

[12] Cf. BHANDARI A. et al. (2007), p. 13 f.

3.3.2 Volatilisation

The mass transfer of contaminants from a liquid or solid phase into a gaseous phase is termed volatilisation. Volatilisation may occur to contaminants that are dissolved in the groundwater, sorbed to the soil or are present as NAPLs and can be responsible for significant losses of organic solutes to the vapour phase. The rate and the extent of the solute mass transfer to the vapour phase depend on the water air partition coefficient of the solute or its Henry's law constant. Volatilisation is a significant mass transfer mechanism for contaminants with a Henry's law constant that is greater than 10^{-7}. So, if the subsurface is contaminated with benzene which has a Henry's law constant of $5.49*10^{-3}$, benzene will primarily separate to the vapour phase, whereas a contaminant like phenol with a Henry's law constant of $4*10^{-7}$, will not usually separate to the vapour phase.[13]

3.3.3 Migration as NAPL (Non-aqueous phase liquids)

NAPLs (also known as free phase) are liquids that exist as a separate, immiscible phase when they come in contact with water, they have a wide range of physical properties and are generally classified by specific gravity (which is the density of the NAPL related to water) into light non-aqueous phase liquids (LNAPL) and dense non-aqueous phase liquids (DNAPL). LNAPL have a specific gravity that is smaller than water and are found at the top of the saturated zone and to some extent below the saturated zone, but the buoyancy limits the depth to which LNAPLs can migrate into the groundwater. DNAPLs have a specific gravity that is greater than water and so they migrate to the bottom of the saturated zone until they reach an impermeable layer. Typical examples of DNAPL are halogenated hydrocarbons (especially solvents), coal tar and creosote, polychlorinated biphenyls (PCB) or mixed DNAPLs. [14]

Typical examples of LNAPL are most hydrocarbons, gasoline, diesel, motor oil, lubricating oils and kerosene.

The most important fluid and porous media properties that affect the NAPL migration and the recovery of the NAPL are the following:[15]

- Specific Gravity: The specific gravity is used to divide the NAPL into LNAPL and DNAPL. The specific gravity is important in order to assess the spread of the contaminants within the subsurface. It is also needed for the prediction of the mass of free product that is present in the subsurface.
- Viscosity: Apart from the specific gravity the viscosity is the second most important criteria which is governing the distribution of the NAPL in the subsurface. The viscosity of a fluid describes its internal resistance to flow. The lower the viscosity of the NAPL the easier it is to recover. The viscosity is a very important factor which is responsible for the mobility and the recoverability of NAPLs. The lower the viscosity of the NAPL the more and the faster it spreads

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[13] Cf. BHANDARI A. et al. (2007), p. 16

[14] Cf. KUEPER B. et al (2003), p. 5 ff.

[15] Cf. KALUARACHI J. et al (2000), p.6 ff.

- Interfacial tension: Interfacial tension is an important factor that is responsible for the distribution and the mobility of the liquids in the subsurface. Interfacial tension is inversely related to the size of the pores. The finer the porous media the more free-product is trapped in the pore space.
- Capillary Pressure: The capillary pressure is defined as being the pressure differences between two fluids. Capillary forces limit the movement of the NAPL. The NAPL movement in the subsurface tends to occur at pathways where capillary pressures are low. The capillary pressure is inversely related to the saturation.
- Relative Permeability: The relative permeability of the geological media is a good indicator if it is possible to mobilize the free phase in the subsurface. It is directionally proportional to the saturation.
- Saturation: Saturation is an important criterion which is controlling the mobility of the water and NAPL. In order to be able to flow the NAPL needs to be connected through the pores and the porous media also needs to be saturated. The saturation levels are also used to estimate the mass of NAPL that is present in the subsurface.

In addition to the above mentioned fluid and porous media properties, the volume of NAPL that was released, the area of infiltration, the time duration of the release and the flow conditions also control the subsurface migration of NAPL.

Movement of NAPLs in the Unsaturated Zone

When NAPL is released to the subsurface it migrates downwards under the force of gravity through the unsaturated zone. Water is the wetting fluid within the subsurface; that means that the water is primarily attracted to the solids and forms a continuous coating around them. Therefore, the water occupies the smaller pores and capillary channels within the unsaturated zone. The NAPL migrates through the larger pores, where water is coating the grains and air filling the remaining pores. The NAPL displaces the air and the pores become filled with the NAPL.[16]

Within the subsurface, the NAPL can exist as residual NAPL and as free phase NAPL. NAPL that is trapped within the pore spaces is termed residual NAPL. When the NAPL saturation is higher than the residual saturation and the NAPL is connected through interconnected pores then this is termed free phase NAPL. [17]

Residual saturation values for NAPLs in the unsaturated zone normally have a range from 0.05 to 0.20 where flow is through the matrix, but it will be significantly less where the movement occurs along fissures. The residual NAPL will dissolve slowly into the subsurface and is a long-term source for groundwater contamination. Also most NAPLs have high vapour pressures and where NAPL exists in the unsaturated zone, a plume of solvent vapour develops in the soil air surrounding the NAPL source. These vapours can condense on soil water and cause additional groundwater contamination at the water table. [18]

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[16] Cf. WHITHOME A. et al. (1996), p.8 ff.

[17] Cf. WATER TECHNOLOGY INTERNATIONAL CORPORATION (1997), p. 2

[18] Cf. WHITHOME A. et al. (1996), p. 9 f.

LNAPL and DNAPL movement in the saturated zone

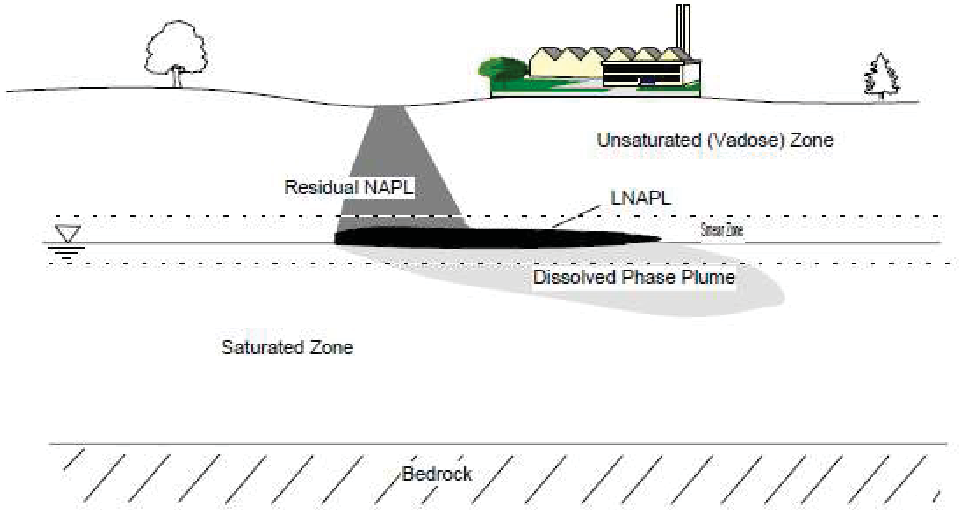
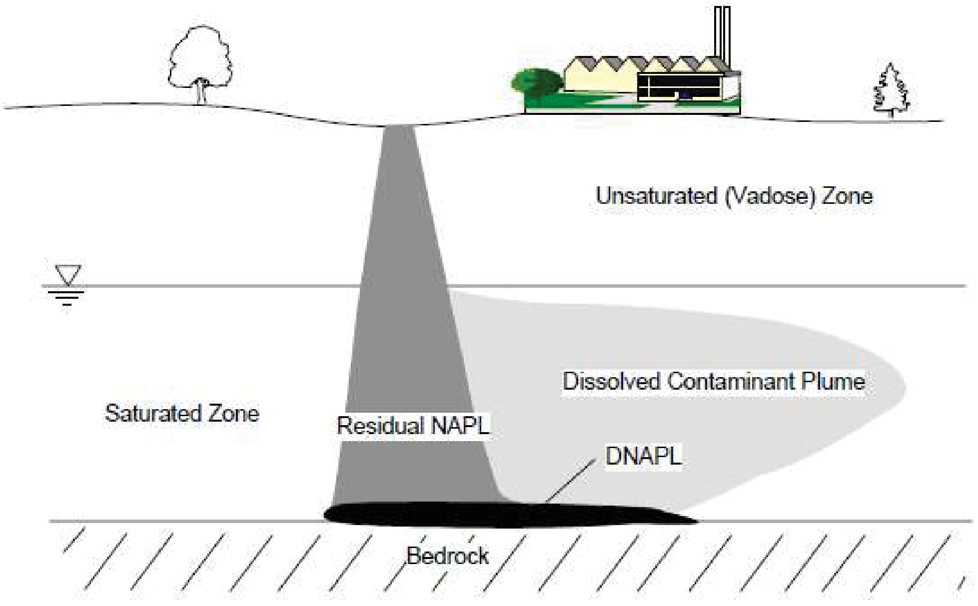


Figure 3: Typical subsurface contamination of a LNAPL[19]

The LNAPL migrates through the unsaturated zone and spreads laterally on the top of the saturated zone. It is important to note that the LNAPL does not float on the water table as a separate layer above the saturated zone but partly submerged in the water like an iceberg in the sea.[20]



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[19] Source: WATER TECHNOLOGY INTERNATIONAL CORPORATION (1997), p. 4

[20] Cf. SCIENCE ADVISORY BOARD (2006), p. 9

Figure 4: Typical subsurface contamination of a DNAPL[21]

The DNAPL migrates vertically in the saturated zone until it reaches an impermeable layer such as the bedrock in the figure above. Once it reaches the impermeable layer it continues to flow laterally under pressure and gravity forces. DNAPL dissolves in the groundwater and acts as a long-term source of groundwater contamination.[22]

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[21] Source: WATER TECHNOLOGY INTERNATIONAL CORPORATION (1997), p. 5

[22] Cf. WHITHOME A. et al. (1996), p. 12

4 Description of Remediation methods

The investigations which were carried out in the former chapter serve as a basis for better understanding the environment in which remediation methods are applied. It can be noted that there is much literature available which provide a detailed description of the remediation methods which are subsequently assessed. However, within this thesis, I focussed intentionally on providing a short overview of the most important decision criteria which govern whether a remediation method is applicable, for the specific circumstances which prevail at a contaminated site. The overview consists of a technical description of the remediation methods; it also covers the specific circumstances and limitations under which these methods can be applied and also gives information about which factors govern the costs of the investigated methods. For the following descriptions many different sources, which have been used intentionally, provide information for both the investigated as well as the non-investigated remediation methods. These sources provide a good basis for in-depth information. Aside from the sources which were used, especially the publications from EPA, are also good information sources for additional information. Principally, you can decide between situ remediation methods that remediate the unsaturated zone, the saturated zone and methods that are applicable for both zones. There are many technologies available and there is rapid development of new technologies in this field. In this section, I will give an overview of the most commonly used remediation methods, which also have a long standing record in the industry.

For the unsaturated zone the following remediation method will be explored:

- Soil vapour extraction
- Bioventing

For the saturated zone the following remediation methods will be explored:

- Pump and treat
- Air sparging
- Permeable treatment walls

For both zones the following remediation methods will be explored:

- Monitored natural attenuation
- Pneumatic or hydraulic fracturing
- Excavation

4.1 Unsaturated zone technologies

4.1.1 Soil vapour extraction (SVE)

Description

Soil vapour extraction is a remediation technology that is used to remove volatile and semi-volatile organic contaminants from the unsaturated zone. Several extraction wells are placed at locations in and around the contaminated area, and through those extraction wells a vacuum is produced in the subsurface. The vapour phase of the contaminants is extracted due to the vacuum; those vapours are collected and treated by off-gas technologies such as granular activated carbon, thermal oxidation, catalytic oxidation, or scrubbing. SVE can be used with other technologies such as air sparging in order to extend its applicability to the saturated zone.[23]

Applicability

The technology of soil vapour extraction is mainly applicable for VOC with a Henry's Law Constant greater than 10^{-5} [atm*m³/mol], but the biodegradation of VOC with a lower Henry's Law Constant can also be facilitated. SVE works best if the soils are well drained, there are low levels of organic material and a high pneumatic permeability (greater than 10^{-10} [cm²]) present. If the soil lacks a high pneumatic permeability, fracturing can be used in order to increase the pneumatic permeability. Fracturing will be later explained in detail within the remediation methods that are applicable for both zones. SVE is very effective in reducing VOC concentrations in the unsaturated zone below the target levels, often removing between 98-100% of the contamination. The more heterogeneous the site is the more difficult SVE is to apply, but the problem of site heterogeneity can be overcome by a good design and proper location of the extraction wells. [24]

Limitations

Factors which may limit the applicability of SVE include:

- SVE is limited to permeable unsaturated materials like sands, gravels and coarse silts.[25]
- Soils which consist of consolidated material and have a high degree of saturation will require a higher vacuum which consequently means higher costs.
- If the subsurface consists of soil that is extremely dry or has a high organic content, this results in a high sorption capacity of the VOCs, which consequently leads to reduced removal rates.

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[23] Cf. EPA (2001), p. 4-1

[25] Cf. WATER TECHNOLOGY INTERNATIONAL CORPORATION (1997), p. 12

- The polluted air that is recovered from the SVE system requires treatment to eliminate possible risks to the public and the environment (the treatment of the air can largely contribute to the overall cost depending on the type of treatment that is required).[26]

Costs

Generally, the clean up goals, the concentration, mass and distribution of the contaminants, the geology and the heterogeneity of the subsurface determine the costs of the SVE equipment that is necessary for successfully remediating the site. These factors are responsible for the number of extraction wells, the vacuum level that is required, the type of off-gas treatment and the period of time that is needed for the treatment.[27]

4.1.2 Bioventing

Description

Bioventing is a remediation technology which degrades contaminants that are absorbed to the soil with the help of micro organisms that exist within the subsurface. The activity of the micro organisms is facilitated by inducing oxygen in the unsaturated zone by using extraction or injection wells. If necessary, nutrients are added to the oxygen which can accelerate the degradation of the contaminants. It can be noted that the Bioventing technology is quite similar to the technology that is used for soil vapour extraction. The main difference is that SVE removes the contaminants primarily through volatilisation while Bioventing systems facilitate the biodegradation of the contaminants and minimises volatilisation by using lower air flow rates than SVE. Nevertheless, both processes (volatilisation and biodegradation) occur when SVE or Bioventing is applied.[28]

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[26] Cf. UYESUGI et al (1994), p.4-25

[27] Cf. EPA (2004), p. 4-15

[28] Cf. UYESUGI et al (1994), p.4-5 f.

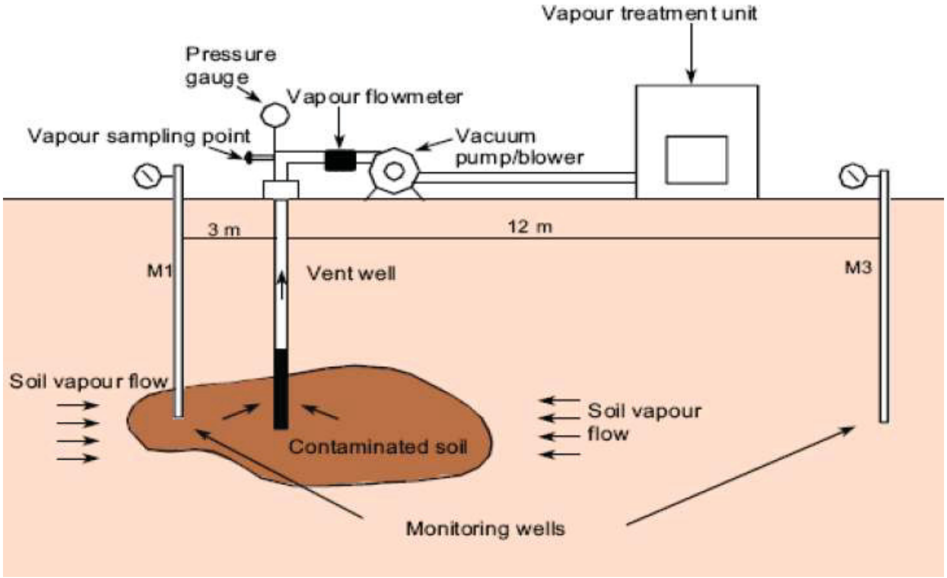

Figure 5: Bioventing system[29]

Applicability

Bioventing can be successfully combined with other technologies such as air sparging or groundwater extraction. Off-gas treatment is not necessarily required for the application of a Bioventing system. [30]

Generally Bioventing is applicable to most hydrocarbons as long as they are biodegradable. The vapour pressure of the contaminants governs the applicability of Bioventing for a contaminated site. Contaminants, such as benzene, toluene, or xylenes, with a vapour pressure in between 1 – 760 mm Hg are best suited for the application of Bioventing. [31]

Limitations

Factors which may limit the applicability of Bioventing include: [32]

- Low permeability soils, extremely low moisture content and low temperatures generally limit the performance of Bioventing.
- Because biodegradation is a slow process, at least two years are required for the remediation of the site. So, if there are time constraints present, Bioventing might not be a suitable remediation technology.
- It is difficult to predict the amount of emissions that are generated when Bioventing is applied at a contaminated site. It is often not sure if off-gas treatment is required. When off gas treatment is needed, this can contribute to a large extent to the overall costs and consequently can limit the applicability of Bioventing.

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[29] Source: URL: http://www.wrc.org.za

[30] Cf. EPA Bioventing (1994), p.3-1

[31] Cf. NORRIS R. (1993), p.3-6

[32] Cf. NORRIS R. (1993), p.3-17

- High concentrations of contaminants can be toxic to micro organisms

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Costs

Concerning the installation costs of a Bioventing system it can be said that the erection of the injection and extraction wells are the main cost causer for a Bioventing system. The amount of wells that has to be installed is mainly dependent on the contaminated volume and the types of contaminants that are present within the subsurface.

The key cost causer within the operating costs of a Bioventing system are the monitoring costs. The rates at which the biodegradation occurs has to be monitored and consequently adjusted in order to guarantee an optimal biodegradation rates. The costs that apply for monitoring are depending very strong on site specific issues such as the soil permeability or the rate of oxygen that has to be delivered.[33]

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[33] Cf. NORRIS R. (1993), p.3-17

4.2 Saturated zone technologies

4.2.1 Pump and treat

Description

Pump and treat is a remediation method, where contaminated fluids are extracted from the aquifer and subsequently treated. A typical pump and treat system consists of a trench, a recovery well (which is normally placed in the centre of the trench), a pump (attached at the bottom of the recovery well), and associated equipment for the treatment of the extracted groundwater such as separators, air strippers or carbon absorbers. The pump lowers the groundwater table near the extraction well and the NAPL and the contaminated groundwater are skimmed off inside the well and pumped to the separator for further treatment. Generally, pump and treat can be used either to achieve source control (for hydraulically containment) or for active decontamination measures.[34]

When pump and treat is used to achieve source control the main goal is to hydraulically control the movement of contaminated groundwater to previously uncontaminated areas. Hydraulic containment is often chosen when the contaminants can not be recovered e.g. DNAPLs in fractured rocks. When active decontamination measures are applied, the goal of pump and treat is to recover and treat the contaminants and discharge them in compliance with existing regulations. It has to be noted that depending on the subsurface conditions and on the properties of the contaminants only a part of the contaminants can be recovered, whereas the remaining contaminants are not recoverable and remain in the subsurface as residual contamination which continues to be a long-term source of contamination.[35]

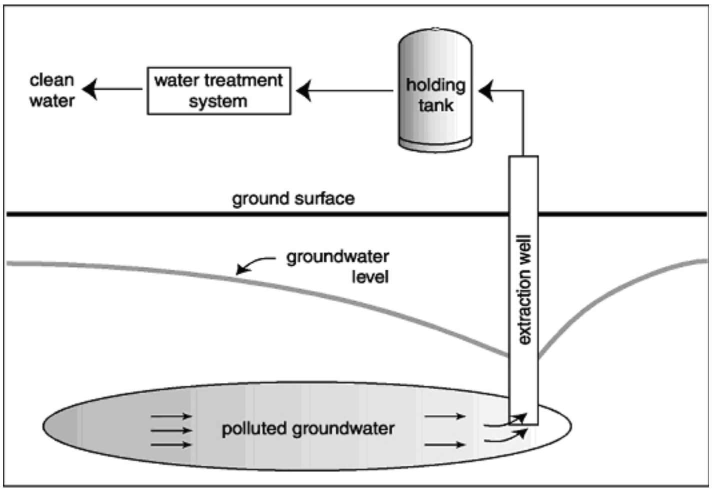

Figure 6: Pump and treat system[36]

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[34] Cf. COHEN R. et al. (1997), p.2 f.

[35] Cf. BHANDARI A. et al. (2007), p. 47 f.

[36] Source: URL: www.epa.gov

Equipment that can be used for the treatment of contaminated groundwater

The equipment which is subsequently described is not exclusively applicable for sites where pump and treat is used for the remediation of the contaminated subsurface but also for all remediation technologies where contaminated groundwater is extracted and treated further. There is also other equipment (such as advanced oxidation, bioreactors or membrane separation) which can be used for the purification of contaminated groundwater. But this kind of equipment is not as commonly used as separators, air strippers and carbon adsorption. This is the reason why it will not be analysed in this thesis.

Separator

A separator extracts the NAPL from the fluid which comes from the recovery well. The fluid enters the separator and the NAPL is skimmed off at the top of the separator while the groundwater leaves at the bottom. Separators are only used to separate the immiscible phase from the extracted groundwater. The separation process works because water and the NAPL have different densities. Separators are a proven technology; they are inexpensive to operate and require little maintenance and are especially used for separating water from petroleum products such as oil and gasoline. A main disadvantage of separators is that they do not remove dissolved contaminants. Air strippers can be used for the removal of contaminants which are dissolved in the groundwater.[37]

Air strippers

Air stripping is a method where volatile organic contaminants (which are dissolved in the groundwater) are transferred from the aqueous phase to the vapour phase. A typical air stripper system consists of a tower, air blowers, pumps and piping and distribution systems. An air blower is installed at the bottom of the tower; the air blower forces the air to the top of the tower. The extracted fluids enter at the top of the tower and come into contact with the air while flowing to the bottom. Through this process, the volatile organic contaminants are transferred from the liquid phase to the vapour phase. The treated water which leaves the tower is discharged to sewers or treated further with the help of carbon absorbers (if drinking water levels want to be achieved). The air emissions that contain organic contaminants may also require treatment depending on the regulations. Air strippers are a proven technology; they can be installed quickly and need little maintenance. They are very successful for removing soluble contaminants with a high volatility. The main disadvantage of air strippers is that fouling by inorganic precipitants might occur. When fouling occurs the strippers have to be maintained, they need to undergo acid wash before they can be used again. In order to prevent fouling, the fluids can be treated by removing the inorganic precipitates before they reach the air stripper.[38]

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[37] Cf. WATER TECHNOLOGY INTERNATIONAL CORPORATION (1997), p. 32 f.

[38] Cf. WATER TECHNOLOGY INTERNATIONAL CORPORATION (1997), p. 34 f.

Carbon Adsorption (Liquid Phase)

The extracted groundwater is pumped through either one, or more commonly, to a few adsorption canisters which contain activated carbon. The dissolved organic contaminants adsorb onto the carbon. Once the carbon is saturated with contaminants the carbon has to be replaced or it has to be thermally regenerated for further use. Drinking water requirements can be reached with the help of carbon adsorption. Carbon adsorption is an efficient method for the treatment of very low contaminant concentrations (< 10 mg/l). Contaminants that can be effectively removed by sorption to activated carbon include petroleum hydrocarbons, VOCs or halogenated VOCs.[39]

Applicability

Pump and treat is the remediation method that is most commonly used for contaminated groundwater. When DNAPL is present in the subsurface, pump and treat is often used for the containment of the contamination with associated partial recovery. When LNAPL is present in the subsurface pump and treat is an effective remediation method especially when the aquifer has a moderate to high hydraulic conductivity. [40]

Limitations

Factors that may limit the applicability of the pump and treat method are:

- Tailing and rebound: When the contaminant concentrations are measured in the groundwater during the monitoring process, often so-called tailing and rebound effects can occur over time. Tailing means that the concentration of the dissolved contaminants declines at a slower rate than the rate that would be theoretical possible. The term rebound means that once pumping is stopped (e.g. the set regulatory limits have been reached), the dissolved contaminant concentration starts to rise again after some time, as also shown in the next figure. The reason behind the tailing and rebound effects is the slow mass transfer from the residual contamination to the groundwater. Other reasons for the tailing include changing groundwater velocities, flow path variations and the slow diffusion of the contaminants from low permeable zones.[41]

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[39] Cf. BHANDARI A. et al. (2007), p. 102

[41] Cf. COHEN R. et al. (1997), p.5

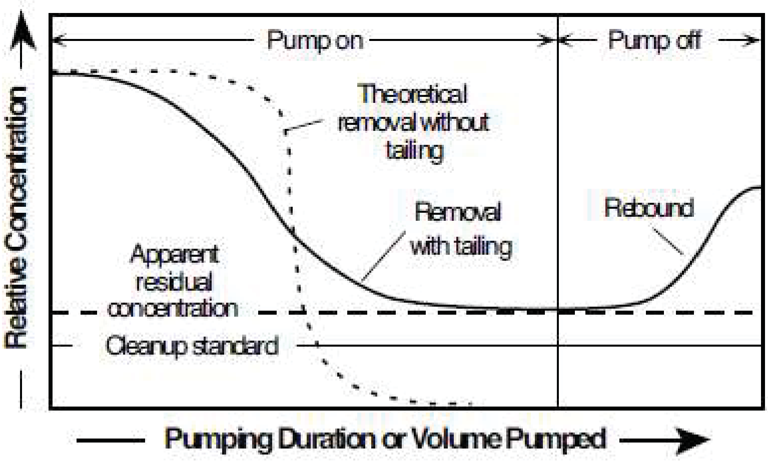

Figure 7: Concentration versus pumping duration[42]

- The remediation of contaminated groundwater, with the help of pump and treat, usually needs a very long time frame compared to other remediation methods.
- Pump and treat is not able to remove the residual saturation within the subsurface.
- Generally, drinking water requirements are not reached with the application of pump and treat.[43]

Costs

The EPA compared the costs of 32 pump and treat projects. The coherence between unit capital costs and volume of groundwater that was treated per year was obvious. Unit capital costs ($/1.000 gallons/ year) generally decreased when larger amounts of groundwater where treated as shown by the next figure.[44]

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[42] Source: COHEN R. et al. (1997), p.5

[43] Cf. KALUARACHI J. et al (2000), p.79 ff.

[44] Cf. EPA (2000), p. 6- 6 f.

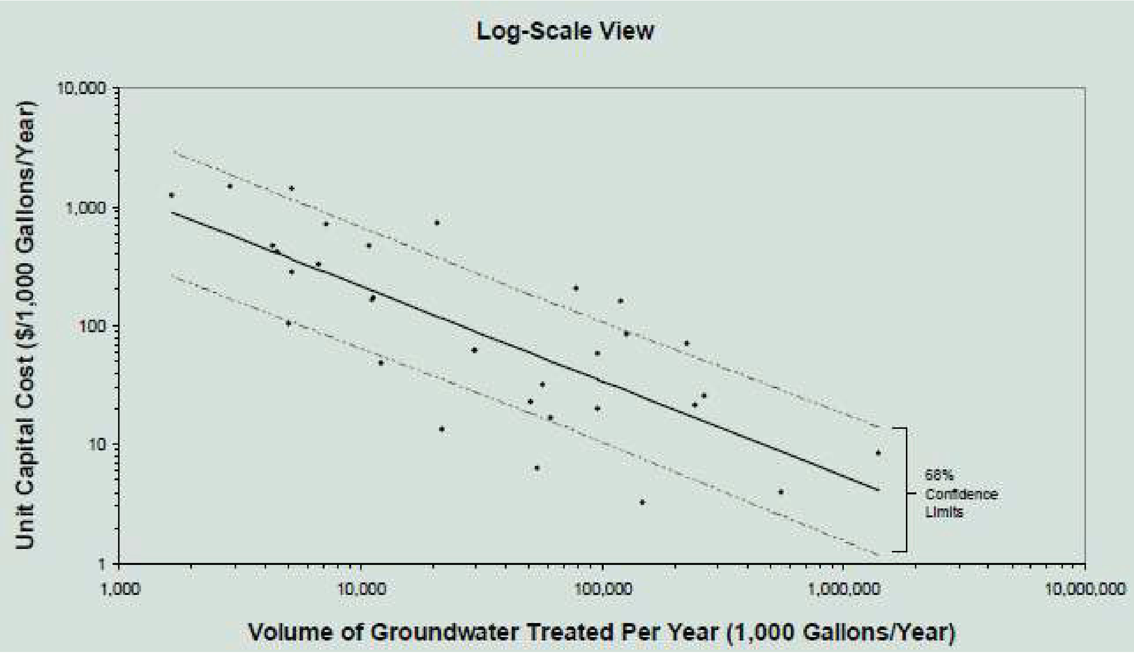

Figure 8: Unit Capital Cost versus Volume of Groundwater treated for 32 P&T projects[45]

When the contaminated groundwater is located at a shallow depth, and limited to a small area, it is normally easier and cheaper to remediate than when the same mass of contaminants are located deeper and extended over a larger area. This is because the depth and the areal extent of the contamination govern the size of the extraction and the overall treatment system. The kinds of contaminants that are present in the subsurface also influence the costs of a pump and treat system. From the 32 P&T sites that where investigated, it can be concluded that the capital and annual operating costs were less for sites where VOCs were present than for sites where combinations of contaminants such as BTEX, PCBs or PAHs were found. Also the above ground treatment equipment that is used affects the costs of the P&T system. When less above ground treatment equipment is used, the overall costs are generally lower for the P&T system.[46]

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[45] Source: EPA (2000), p. 6.7

[46] Cf. EPA (2001), p.1 ff.

4.2.2 Air Sparging

Description

When the technology of air sparging is applied, oxygen is injected through a well into the saturated zone. This has two effects; the first effect is that the aerobic biodegradation of the contaminants is encouraged because of the oxygen that is being added. The second effect is that the contaminants that are dissolved in the groundwater, and contaminants that are sorbed to the soil, are volatilised. The volatilised contaminants migrate to the unsaturated zone and can then be, if necessary, recovered by a soil vapour system.[47]

It can be said that the air sparging technology is extending the applicability of the SVE from the unsaturated to the saturated zone. Depending on the conditions that prevail on the site, off-gas treatment might be needed, but if the injection and the extraction rates are properly adjusted this can significantly reduce and sometimes even eliminate the need for off-gas treatment. Air sparging can also be combined with other technologies such as pump and treat or monitored natural attenuation. Sometimes air sparging is also referred to as bioremediation. This term is often applied when biodegradation (and not volatilisation) is the main remediation process that is present at the contaminated site.[48]

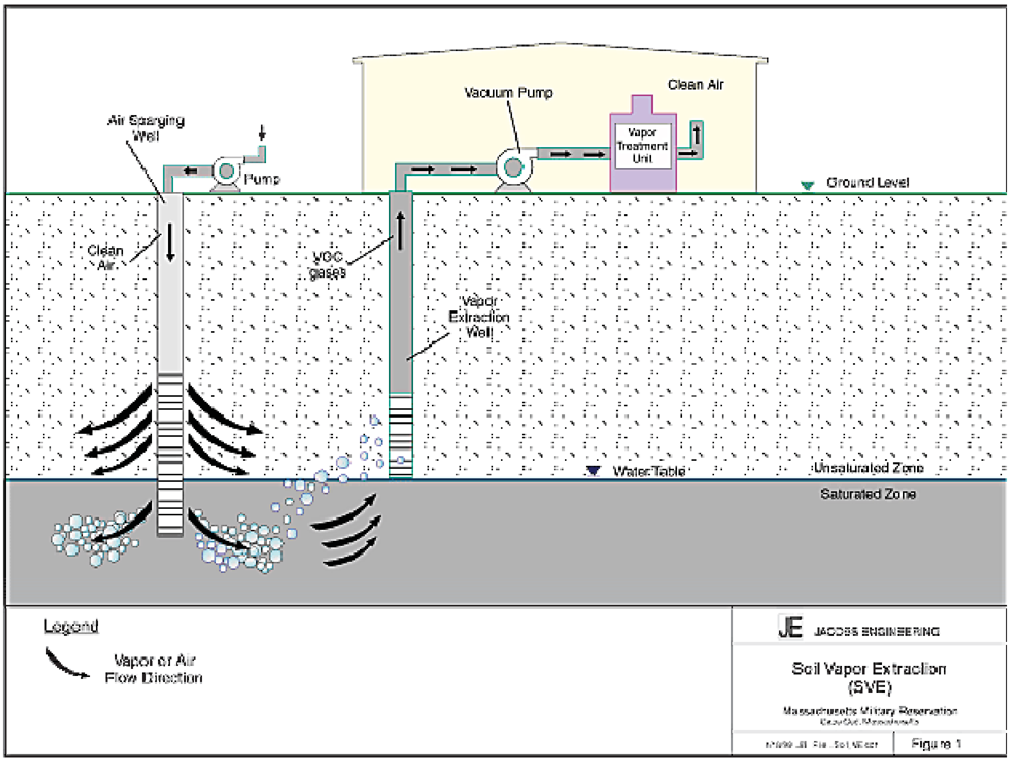

Figure 9: Air sparging system[49]

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[47] Cf. BARDOS P. et al. (2003), p.42

[48] Cf. MILLER R. (1996), p.1 ff

[49] Source: URL: http://www.mmr.org

Applicability

Generally, the air sparging technology can be applied to volatile, semi-volatile and non-volatile contaminants as long as they are biodegradable within the unsaturated zone. The contaminants can be present as NAPL, dissolved into the groundwater, sorbed to the soil or in the vapour phase. In can be noted that a homogenous subsurface is favourable for the application of an air sparging system. Nevertheless, the most important property of the subsurface is its ability to transmit the injected oxygen. In other words, the higher the permeability of the subsurface the better it is suited for the application of air sparging.[50]

Limitations

Factors which may limit the applicability of the air sparging method are:

- The hydraulic conductivity of the subsurface needs to be greater than 10^{-3} cm/sec in order to enable sufficient air flow.
- Low permeability layers within the contaminated area generally limit the application of air sparging because they prevent the vertical flow of the injected air.[51]
- If there are contaminants present in the subsurface that can not be vaporised or that are not biodegradable air sparging is not an appropriate remediation technology.
- If there is NAPL present in the subsurface the application of air sparging can lead to the spread of the contamination.
- When the subsurface is heterogeneous or stratified, air sparging can only be applied to a limited extent because the air tends to move through areas of less resistance, leaving potentially contaminated areas unaffected.[52]

Costs

An important cost factor for an air sparging system is the flow rate of the air that needs to be injected. The flow rate, among other things, is dependent on the kind of contaminants that are present in the subsurface e.g. MtBE needs a much higher flow rate than BTEX. Other issues that affect the costs of an air sparging system include the degree of the contamination, hydrology and geology (permeability, heterogeneity) of the subsurface, depth of the contamination and the clean up goals that are set. These issues affect the costs in that way that they determine the number of air sparging wells, the flow rate that has to be applied and the length of the decontamination measures.[53]

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[50] Cf. MILLER R. (1996), p.3

[51] Cf. P.NYER E. et al. (2001), p. 187 f

[52] Cf. PORTER W., BENNINGTON C. (2008), p.170

[53] Cf. EPA (2004), p. 4-17 f.

4.2.3 Permeable reactive barrier

Description

A permeable reactive barrier is erected in the direction of the groundwater flow. The contaminated groundwater flows through the reactive material and the contaminants are either degraded or immobilised by the reactive material within the PRB. PRB is, such as pump and treat, a pathway management technique. The goal of a pathway management technique is to prevent the flow of contaminants to previously uncontaminated areas. This is achieved through physical, chemical or biological processes that can be applied within the barrier. The permeability of the PRB should be at least a factor two higher than the permeability of the surrounding subsurface, but a higher permeability factor is generally favourable because during the lifetime of the system the permeability of the system is reduced due to several factors such as the settling of fine soil particles within the PRB, the precipitation of carbons, oxides or hydroxides or the uncontrolled growth of micro organisms.[54] PRB can be divided into two major subcategories, funnel and gate and continuous trench. In a funnel and gate application impermeable walls are erected that direct the contaminated groundwater through a gate which contains the reactive material that is used for the treatment of the contaminants. In contrast, a continuous trench configuration involves erecting a trench, which is filled with the reactive material, across the entire path of the contamination plume.[55]

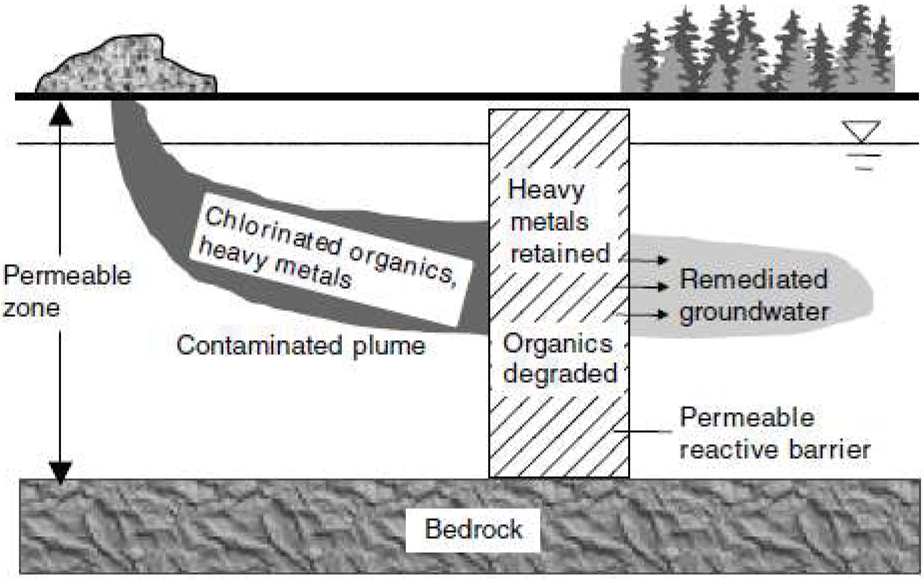

Figure 10: Groundwater remediation using PRB[56]

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[54] Cf. BARDOS P. et al. (2003), p.48 f.

[55] Cf. EPA (2001), p.3

[56] Source: SIMON F. et al., p.7

Applicability

PRB is a suitable remediation technology for the treatment of VOC and SVOC, and it can also be used (but is less effective) for the treatment of fuel hydrocarbons. It can be successfully applied to contaminants that are dissolved in the groundwater, to contaminants that have a mobile phase and to contamination plumes that are heterogeneous in concentration and composition.[57]

Limitations

Factors which may limit the applicability of a permeable reactive barrier are:[58]

- PRB is not a good remediation technology for insoluble or immobile contaminants.
- A long treatment time is likely if a low groundwater velocity or a low hydraulic conductivity is present in the subsurface.
- Permeability of the reactive material can be significantly reduced by precipitation.

Costs

The costs of a PRB are mainly dependent on the areal extent of the contamination plume and the reactive material that is needed for the erection of the barrier. The installation costs of PRB are usually much higher than the installation costs of a pump and treat system of comparable size, but the operating costs of a permeable reactive barrier are expected to be much lower than the pump and treat system of comparable size. However, recent studies that have been carried out, which compare the costs of PRB with P&T sites, have shown that the cost savings in the operating costs are not as much as it was believed when the first PRB were erected.[59]

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[57] Cf. MOUNTJOY K. et al. (2003, p.3

[58] Cf. MOUNTJOY K. et al. (2003, p.3

[59] Cf. POWELL M., POWELL D. (2002), p.2

4.3 Methods suitable for both zones

4.3.1 Fracturing

Description

Fracturing is used to enhance the recovery rate of contaminants in soils which consist of a low permeability. For remediation applications either pressurised air (for pneumatic fracturing) or fluids (for hydraulic fracturing) are injected into the subsurface in order to generate fractures. Shortly after the fracturing process, a slurry which mainly consists of granular material (sand) or gel is pumped into the newly-formed fractures. This material keeps the fractures open and highly permeable channels are created which are responsible for the enhanced recovery of the contaminants. [60]

Applicability

Fracturing is used to increase the permeability of the subsurface and enhance the performance of a variety of remediation methods such as air sparging, soil vapour extraction or pump and treat.

The technology of fracturing is applicable to all contaminants. It is used mainly for the fracturing of soils that consist of silts, clays or shale. It can be noted that it is most effective for silt and clay because they have the lowest hydraulic conductivity in respective of permeability. Fracturing however is very occasionally used for the purpose of remediation.[61]

Limitations

When fracturing is applied at a contaminated site, it is possible that new pathways will be generated which may facilitate the spread of contaminants to previously uncontaminated areas. Also refracturing might be necessary especially for sites where remediation measures are scheduled for longer periods.

Costs

There is not much cost difference between hydraulic and pneumatic fracturing, although hydraulic fracturing might be slightly more expensive because additional costs accumulate for the equipment that is necessary for the mixing of the injection slurry. The most important factors that are responsible for the cost of fracturing are site specific issues such as the soil properties, depth of the contamination, depth of the groundwater and the areal extent of the contamination.[62]

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[60] Cf. WATER TECHNOLOGY INTERNATIONAL CORPORATION (1997), p. 18

[61] Cf. EPA (1997), p. 6 -2 ff.

[62] Cf. EPA (1997), p. 6 -18 ff.

4.3.2 Monitored Natural Attenuation

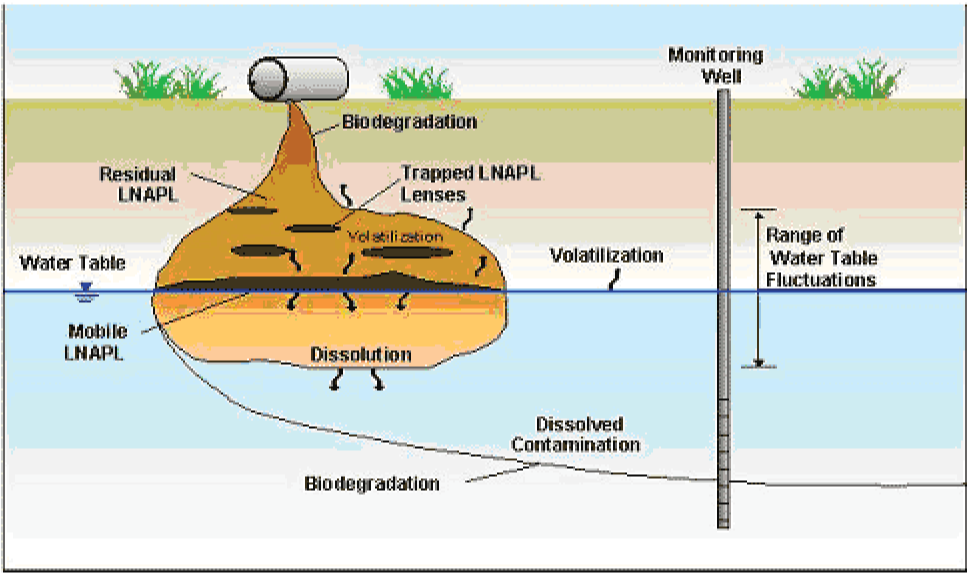

Figure 11: Monitored Natural Attenuation [63]

Description

The natural attenuation of contaminants can be facilitated through processes such as dilution, volatilisation, biodegradation, adsorption or chemical reactions of the contaminants with the subsurface material. These processes can eventually reduce the contaminant concentrations to levels that are acceptable for the responsible authorities. The goal of MNA is to demonstrate that natural attenuation occurs at an acceptable rate which finally leads to contaminant concentrations which are below those set from the responsible authorities. [64]

Applicability

Monitored Natural Attenuation is applicable to sites where the contaminants are sorbed to the soil and are not migrating. VOC and SVOC and fuel hydrocarbons are contaminants that can be effectively reduced by natural attenuation, whereas halogenated VOCs and SVOCs are not suited for the natural attenuation process. MNA is used at sites where other remediation methods are not significantly faster than the natural attenuation of the contaminants and/or where the removal of the contaminants is technically not possible.[65]

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[63] Source: HARDISTY P, OZDEMIROGLU, p.48

[64] Cf. WHITHOME A et al. (1996) , p.100

[65] Cf. WHITHOME A et al. (1996) , p.100

Limitations

Factors which may limit the applicability of MNA include:

- Usually much more time is required to achieve remediation objectives compared to active remediation measures.
- The degradation products can be even more toxic and/or mobile than the original contaminants.[66]
- The origin of the contamination (source) might have to be removed before MNA can be chosen as an appropriate remediation technology.
- MNA is not a suitable remediation technology if NAPLs are present in the subsurface, because the contaminants could migrate before they are degraded.
- The costs that accumulate for the site investigation are likely to be more expensive, compared to other remediation technologies, because not only the contaminants that are known to be present in the subsurface have to be investigated, but also the degradation products (which form due the natural attenuation) have to be investigated.[67]

Costs

Costs accumulate for the analysis of the contaminants. It has to be analysed if the degradation products pose a risk to the surrounding environment and consequently if monitored natural attenuation is an appropriate remediation technology for the site. Other costs include the costs that accumulate for site characterisation. During site characterisation, information about the areal extent of the contamination and the degradation rates are gathered. Once MNA has been chosen for the contaminated site, the costs mainly consist of monitoring the performance of the contaminants. Performance monitoring gives information about the migration of the contaminants and current degradation rates, and mainly consists of collecting and analysing the collected samples.[68]

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[66] Cf. EPA (2004), p. 5-2

[67] Cf. WYCKOFF et al. (2000), p.59

[68] Cf. UYESUGI et al (1994), p.4-29

4.3.3 Excavation

Description

The contaminated volume is excavated and then refilled with clean material. The contaminated material is brought to disposal facilities. Excavation and off-site disposal is a well-proven technology.

Depending on the degree of contamination a pre-treatment, prior to the disposal, may be obligatory.[69]

Applicability

Excavation and off-site disposal is applicable to all kinds of contaminants.

Limitations

Factors which may limit the applicability of excavation include: [70]

- The generation of fugitive emissions can be a problem (especially for workers) during the excavation process.
- Compared to insitu methods, excavation is only economical for small contaminated volumes.
- Transportation of the soil through populated areas might be a problem for the public.

Costs

The costs that accumulate for excavation and disposal mainly depend on the transport distance (from the contaminated site to the disposal facility), degree of contamination (disposal charges) and the depth to which the contaminated soil has to be excavated (excavation costs increase with increasing contamination depth).

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[69] Cf. WHITHOME A et al. (1996) , p.98

[70] Cf. COLEY M. (1994), p.238

5 Decision making issues

This chapter is particularly useful for decision makers; it provides important underlying information which is essential for an integrated view of contaminated land problems. There are several factors which have to be considered when selecting an effective remediation solution for contaminated land. These key factors provide a combination of technical, social and economic information which is important for treating contaminated sites.

In this chapter, key factors that one should give additional thought to before choosing an appropriate remediation method for a contaminated site, are summarised:

- Risk management
- Sustainable development
- Stakeholder satisfaction
- Cost and benefits
- Technical feasibility/suitability

These key factors will be subsequently investigated in detail within this chapter. Understanding the key factors and their interactions is absolutely vital for a contaminated land manager in order to come to a qualified decision for a particular remediation technology. This chapter also provides a framework for the assessment of a remediation technology for a contaminated site. The aim of this framework is to provide an example of how decision support can be carried out.

There are many reasons why remediation of a contaminated site takes place. In the following, an overview is provided on the most important reasons for the implementation of remediation measures. The main reason why remediation measures are carried out is the protection of human health and the environment which is effected by contamination. If the threshold values (which are set by responsible authorities) for human health or the environment are exceeded at a contaminated site then remediation will be mandatory. Another reason for the execution of remediation measures is to repair or expand already existing remediation projects. These actions often have to be carried out because the initial site investigation was deficient. Sometimes, remediation is carried out because of economic issues. A contaminated property has less monetary value than a remediated property. So, if the costs that accumulate for remediation are less than the gains in land value, it is economical to remediate. Reducing potential liabilities can also be a driving force for the execution of remediation measuers.[71]

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[71] Cf. BARDOS P. et al. (2002), p. 137

5.1 Risk management

The risk management process starts with a site investigation of the contaminated land. Information is gathered about the potential risks which might be present to human health or to ecosystems or to both. The collected data should provide general information like the circumstances of how the contamination occurred, the types of contaminants that are present within the subsurface, the hydro geological which prevail in the subsurface or the extent of the contamination plume. After the site investigation, the risks to human health or ecosystems are analysed. There are three options that are generally viable at this stage: undertaking remediation measuers, monitoring of the site or no remediation measuers. If remediation measuers have to be implemented, the costs, advantages and disadvantages of the remediation options need to be weighed up.[72]

Concerning contaminated sites, a risk is said to be present when a source, a pathway and a receptor exist within the subsurface and these elements are connected to one another. When the above mentioned elements are found at a contaminated site they form a so-called pollutant linkage. The main goal of the risk management process is to evaluate how the pollutant linkage can be broken in order to eliminate or at least reduce the risks that are present at the contaminated site. Generally, there are three possibilities how this action can be achieved. The first possibility is to reduce the source of the contamination. This can be achieved by remediation methods such as excavation, soil vapour extraction or Bioventing. The second possibility is to treat the contaminants at the pathway (which is usually the groundwater) they are travelling. The goal of pathway remediation technologies is to prevent the further movement of the contaminants into previous uncontaminated areas and to remediate the contaminants which are present within the subsurface. Typical examples of pathway management remediation technologies include pump and treat and permeable reactive barriers. The last possibility to reduce or eliminate the risk is to modify the exposure to the receptor; this can be achieved, for example, by preventing the site access to the contaminated area or by restricting the land use. Once it is decided which action (source reduction, pathway management or modifying the receptor) should be chosen for the remediation of the site, remediation options and their probability for a successful remediation, are evaluated. Apart from the probability of success, other factors such as sustainable development, cost effectiveness of the remediation options, stakeholder concerns, technical suitability and feasibility are also being evaluated.[73]

These factors are subsequently investigated in this chapter.

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[72] Cf. PCCRARM (1997), p.1 f.

[73] Cf. BARDOS P. et al. (2002), p. 139 f

5.2 Sustainable development

It can be noted that sustainable development is a combination of three factors: economic growth, environmental protection and social progress. Generally, the goal of sustainable development is facilitated when decontamination measuers are carried out, however each remediation option has its very own impact on sustainability issues. Which remediaton method is realisable is dependent on specific constraints such as time and money available for remediation measuers, the possibility of placing equipment necessary for the remediation and the planned land use (after remediation measures have been carried out). Which remediation methods are generally qualified for successful decontamination are ultimately chosen as a result of site specific constraints and moreover as a result of stakeholder consultations. During the decision making process, site specific goals (which need to be achieved for the successful remediation of the contaminated site) are set out, and it can be said that these goals represent the core objectives of the overall remediation project. It has to be noted that the core objectives do not take into account the overall impact of the viable remediation options on sustainability issues. In order to see the overall impact of the different remediation options on sustainability, one also has to investigate the non-core considerations. Examples of non-core considerations include wider environmental factors such as traffic, dust, noise, restoration of ecological functions of the contaminated site, wider economic consequences such as impacts on local employment or compensation for the land owner of the contaminated property and wider social consequences such as the removal of blight.[74]

Essentially, it can be said that the core considerations are determined within the decision making process and these must be mandatory satisfied by the remediation options, however the non-core considerations are variable depending on the remediation options used. So, in the context of sustainable development, it can be said that the most appropriate remediation option is able to fulfil the core objectives and offers the best combination of the wider economic, environmental and social effects for the particular site. Nevertheless, this should not result in choosing a significantly more expensive remediation method over other remediation methods in order to achieve the highest sustainability. If however costs between remediation options do not severely deviate from one another, then the advantages/disadvantages of these remediation methods (with regard to sustainability) should be analysed in detail.[75]

It can be noted that those non-core considerations are becoming more and more important in the decision making process in many countries. There is a general movement of politics to implement sustainability issues. Furthermore there are also specific pressures from stakeholders (such as the avoidance of traffic, noise or dust to the neighbourhood) which promote sustainability issues. [76]

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[74] Cf. BARDOS P. et al. (2002), p. 141 f.

[75] Cf. ENVIRONMENTAL AGENCY (2000), p. 14

[76] Cf. REVIEW OF DECISION SUPPORT TOOLS (2002), p.14 f

5.3 Stakeholder Satisfaction

After the site investigation (which took place during the risk management process) is finished, and the need for remediation has been identified, the potential stakeholders of the contaminated site should be identified and contacted. Stakeholders are individuals or groups which have some kind of interest in the remediation of the contaminated site. The communication with the stakeholders is of major importance for the planning of the decontamination measures. Sometimes the approval of stakeholders (for example the site's neighbours) for issues such as entering their private property is absolutely essential for carrying out remediation measuers.[77]

The following stakeholders are in the centre of the decision making process; a short description of these stakeholders and their potential standpoints is provided in the following: [78]

- Land owners/problem holders: The main goal of problem holders is to remediate the contaminated site as cheaply as possible. Generally, they do not have enhanced interest in remediation methods that are more expensive but show better results concerning sustainability issues.
- Regulators and planners: They are interested that a remediation option is chosen that reaches the screening values that are set by the responsible authorities with a high probability. Of course they will also look that this does not lead to the choice of a remediation option that is significantly more expensive than other remediation options which also have a sufficient probability of reaching the remediation goals.
- Site users, workers: The performance of the remediation options concerning health and safety are the most important issues for site users and workers. They have an interest that the remediation option is chosen which has the best performance regarding health and safety issues.
- Site neighbours: Their main concern is that their quality of life is reduced as less as possible (by noise, dust, or the duration of the decontamination measures) by the remediation measuers. Another important issue for them is that the remediation option that is chosen has a direct effect on the value of the surrounding properties, once the remediation measuers are finished. If excavation (complete removal of the contamination) is performed at a contaminated site, the value of the surrounding properties will be higher compared to pump and treat (there will always be residual contamination left in the subsurface).

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[77] Cf. ENVIRONMENTAL AGENCY (2004), p.9

[78] Cf. ENVIRONMENTAL AGENCY (2000), p.7 ff.

There are also other stakeholders which can be influential such as NGOs, consultants, Technology Vendors and Remediation contractors or researchers but they are not at the core of the decision making process and therefore they will not be discussed in detail here.

As it can be seen in the listing above, the different stakeholders that are involved at a contaminated site have their own view on the attributes that the remediation technology should achieve. The objective of the decision making process is to find a remediation technology that is acceptable for all of the stakeholders that are affected by the contamination whereby one should keep in mind that the most important criteria for the selection of a remediation technology is its ability to get regulatory approval from the responsible authorities. [79]

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[79] Cf. ENVIRONMENTAL AGENCY (2004), p.24

5.4 Costs and Benefits

The costs and benefits that are associated with the remediation options (that are generally viable of remediating the site successfully) form an integral part of the decision making process. Every potentially viable remediation option has its own costs and associated benefits concerning human health, the surrounding environment, the value of the surrounding properties and stakeholder concerns. For some issues, such as the scheduled costs of the remediation options or the gain in land value once the decontamination measures are finished, the process of evaluating the costs and benefits is straight forward and easy to assign. The main problem that is associated with the costs and benefits of the different remediation options is that a monetary value (for issues such as particular stakeholder concerns or the environment) is much more difficult to assign. Issues that are being included or excluded from the assessment of the costs and benefits will vary depending on the site specific circumstances.

There are several tools available which support the assessment of costs and benefits, some put there focus more on environmental factors others more on the associated costs. A short overview of a couple of techniques which are used in contaminated land management is provided in the following:

- Life cycle analysis (LCA): With the help of life cycle analysis the total environmental impact of a remediation technology can be evaluated. LCA is a useful tool in order to estimate the best remediation technology based on environmental aspects. LCA can also be used to find the most polluting, energy consuming or costly steps in a remediation process for the different remediation options.[80]
- Environmental impact assessment (EIA): With the help of EIA the environmental effects that are likely to occur for the different remediation technologies are investigated. As a basis for EIA, a description of environmental aspects that are likely to be significantly affected by the investigated remediation options is needed. According to their relative importance these effects can be weighted and a monetary value can be assigned to the environmental impacts.[81]
- Cost benefit analysis (CBA): The costs of the remediation options are balanced with the benefits. The cost benefit tool will be explained in detail later on within the framework for the assessment of a remediation technology.
- Multi criteria analysis (MCA): The MCA consists of three components: different remediation options for a contaminated site, multiple criteria that need to be compared and a method for the ranking of the criteria. In an MCA different criteria of the remediation options can be compared using different units (such as Euro, tonne, m^3). This is an advantage over CBA where all criteria have to be converted to one unit (€).[82]

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[80] Cf. NORMANN J., ANDERSON- SKÖLD Y. (2006), p.4

[81] Cf. ENVIRONMENTAL AGENCY (2005), p.9

[82] Cf. OECD (2006), p.109

5.5 Technical Suitability and Feasibility

From a technical point of view every remediation technology has a theoretical fit (suitability) and a practical fit (feasibility) for the particular circumstances that are prevalent at the contaminated site. Basically that means that a remediation technology that is generally capable of remediating a site successfully, in other words a suitable technique, is sometimes not feasible at the site because of non-technical issues or subjective considerations of decision-makers.[83]

In order to assess which remediation options are generally suitable to remediate the site successfully a couple of factors need to be considered. First of all the remediation objective has to be determined (as mentioned in the chapter that discussed the application of risk management); either source reduction, pathway management or the protection of receptors are generally viable options. Once the remediation objective has been chosen, a remediation approach (which fulfills the remediation objective) needs to be selected. Remediation approaches describe the way in which remediation objectives can be reached. Typical examples of remediation approaches include biological, chemical or physical, thermal treatment, or containment of the contaminants. Once the remediation approach has been chosen the remediation technologies that are capable of fulfilling the given remediation approach can be listed.

Some factors need to be considered in order to find out if these remediation technologies are suitable for the contaminated site, such as:

- are they applicable to the contaminants that are present in the subsurface
- are they applicable to the geological and hydro-geological conditions that prevail in the subsurface
- can they be successfully implementated over the scheduled duration of the decontamination measures (staring from the planning phase and ending with the after-care)
- are they approved by the responsible authorities

Those remediation technologies which fulfill the above named factors can then be termed suitable remediation technologies. As mentioned before a suitable remediation technology also needs to be feasible in order to be a viable candidate for remediation.

There are many factors which influence the feasibility of remediation options; the most important among them include the previous performance of the remediation technology at comparable sites, the possibility of obtaining valuable data about the previous performance of the technology, the duration and the costs of the technology and the acceptance of the remediation technology for stakeholders. These factors need to be carefully evaluated by decision makers, and only remediation technologies which fulfil the requirements can be termed as being feasibly remediation technologies. Generally, innovative or new remediation technologies raise greater concerns about feasibility than for remediation technologies which have a long standing record in the industry. It has to be noted that innovative or

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[83] Cf. BARDOS P. et al. (2002), p. 157

new technologies will often show better results regarding environmental and/or sustainability issues.[84]

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[84] Cf. BARDOS P. et al. (1999), p. 7 f.

5.6 Decision support

Often the decision making strategy is the most inadequately planned part of the site remediation process. The main problem is that most planners only focus on the selection of a specific remediation technology and do not consider all remediation options that would be generally viable in remediating the site successfully. Decision support techniques can and should be used for all of the key factors (risk management, sustainable development, stakeholder satisfaction, cost and benefits and technical suitability and feasibility) that have been examined prior in this thesis. There are several questions for each of these key factors that need to be raised and answered if a decision support process is carried out. After answering these questions, the decision makers have conditioned information on the advantages and disadvantages for all of the investigated remediation options. It should be noted that not only one person is involved in decision support, but several people who have expertise know-how in the key factors that are being investigated. Another important issue concerning decision support is that the selected approaches should be reproducible and transparent, that means that the same approaches (e.g. same set of questions) are used for every contaminated site investigated. All the information that is gained from already existing projects has to be stored. The stored knowledge is helpful for the investigation of future remediation projects. For example, consider a contaminated site, where the volume of soil that has to be treated is being investigated. The analysts would start to collect data concerning the contaminated site such as the areal extent of the contamination or the types of contaminants that need to be treated. Analysts use the stored knowledge in order to get a better estimate of how much soil volume has to be treated (e.g. How was the volume of soil that requires treatment calculated in previous projects?).

The same technique of stored knowledge can be applied by other analysts in the key factors they are investigating such as:

- Costs of the remediation options
- Probability of success for the options
- Stakeholder concerns
- Sustainability issues

Essentially it can be said that the stored information provides planners with useful information (such as the costs of previous pump and treat projects, performance of technology, environmental issues etc.) and helps them to improve the assessment of the project they are currently investigating. The more stored information that exists, the better the analysts' prediction is concerning the remediation of contaminated site. When the decision support process has been finished, the decision-makers are provided with all the advantages and disadvantages of the investigated remediation options and they are able to make a qualified decision on which of the options should be finally implemented. In conclusion, it can be said that it is the goal of decision support to provide the decision-maker with options that are technically and economically feasible, accepted by the responsible authorities and stakeholders. An example of how decision support can be carried out for the choice of a particular remediation technology is provided within the following framework.

5.7 Framework for the assessment of a remediation technology

The previous sections within the fourth chapter highlighted the theoretical basis which needs to be considered in order to choose the most appropriate remediation option for a contaminated site. In this subchapter, the whole decision support process is exemplarily shown in the following framework. Generally, the need to use decision support tools has been realised within the industry (i.e. companies which handle contaminated land problems). There has also been a development of many new decision support tools during the last years and there are many different literature sources which can be used as a basis of decision-making. In this context the following tools can be mentioned: Life Cycle Assessment, Cost Benefit Analysis, Multi Attribute Analysis, Multi-Criteria Analysis or Financial Risk Management. Generally decision support tools can be used just for single aspects of a contaminated land problem, such as for any single key factor that was previously investigated, or they can be used for the whole decision making process, starting from the site investigation and ending with the selection of a specific remediation technology for a contaminated site. The biggest advantage of the described framework is that it uses different decision support tools (such as Qualitative Assessment, Cost Benefit Analysis, Multi Criteria Analysis) which, in combination, lead to a systemic approach and finally to the selection of a remediation technology.

Within this framework, the source-pathway-receptor model which was previously discussed (in the subchapter risk management) is used.

Different levels (policy objectives, remediation objectives, remediation approaches and remediation technologies) have to be distinguished at which decisions concerning the remediation of a contaminated site can be made. A short description of these different decision levels is provided in the following: Policy objectives describe the superior goals that are set by the responsible authorities (such as the remediation goals which need to be achieved in order to remediate the site successfully). Remediation objectives define what actions have to be performed in order to reach the remediation goals set by the responsible authorities. Typical examples of remediation objectives include the hydraulic containment of the contamination, clearance of the contamination to a certain level or the protection of certain receptors. Remediation approaches describe the way in which the remediation objectives can be reached. For that purpose the concept of pollutant linkage (source – pathway – receptor) is used. Typical examples of remediation approaches include: source approaches (such as the source removal to a certain degree), pathway approaches (such as the containment of the contamination plume or the treatment of the contamination plume to a certain degree) or receptor approaches (such as the treatment at the receptor). Remediation technologies are then used to implement the remediation approach. If for example the pathway approach “treat the contaminated plume” is chosen a variety of remediation technologies such as pump and treat or permeable reactive barriers can be applied.[85]

The definition of the different levels at which remediation decisions are carried out is important because these levels will be used later within this framework.

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[85] Cf. HARDISTY P., OZDEMIROGLU E. (2000), p.10 ff.

The framework for the assessment of a remediation technology consists of five basic steps which are shortly explained in the following:

1. Screening Stage
2. Qualitative Analysis
3. Cost Efficiency Analysis/Multi Criteria Analysis
4. Cost Benefit Analyses
5. Sensitivity Analysis

Within the screening phase, the characteristics of the contamination and remediation options that would be generally viable to remediate the site successfully are assessed. The qualitative analysis investigates, with a set of given questions, the effects of the remediation options concerning human health, environment, stakeholder concerns and land use. Within the qualitative analysis these effects are only documented and not rated. After the qualitative assessment, a multi-criteria/cost effectiveness analysis is carried out. The goal of the multi-criteria analysis is to score the issues that have been investigated in the qualitative analysis according to their relative importance; every remediation option receives a particular score which is expressed with the help of a point system. The costs of the remediation options are then divided by the total score that was investigated in the multi criteria analysis. As a result, the remediation options can then be ranked according to their cost effectiveness. A cost benefit analysis is carried out after the multi-criteria/cost-effectiveness analysis. Within the cost benefit analysis those issues that can be valued in money (such as the gain in land value) are assessed for the remediation options in order to obtain a better picture of the economic considerations of remediation options. The last step of the framework consists of a sensitivity analysis, where the key assumptions which were applied within the framework can be altered, in order to see if the altered assumptions have an impact on the ranking of remediation options.

5.7.1 Step 1: Screening Phase

Within the screening phase the areal extent, characteristics of the contamination and the solutions that might be appropriate for its remediation are evaluated. Non-economic issues such as legal regulations from the responsible authorities, sustainability or stakeholder concerns, which form a very important part of the decision making process, are also carefully evaluated during the screening phase. One of the goals of the screening phase is to find a remediation objective which is acceptable to all stakeholders that are involved in the decision making process. This can be achieved by choosing a number of objectives that reflect the minimum requirements of the affected stakeholders. This procedure assures that a range of acceptable objectives will emerge and a final objective can be chosen based on the input of the stakeholders. In addition to stakeholder requirements, the costs that are associated with a certain remediation objective and the results of the negotiations with responsible authorities are the most important issues that affect the choice of the final remediation objective. Of course, there can be constraints which can also influence the choice of the final remediation objective such as: time constraints (e.g. the remediation measures need to be finished within a certain time frame), physical constraints (e.g. there may be constraints for certain objectives such as the placing of equipment in populated areas or other issues which impede full access to the contaminated site), or technical constraints (certain remediation objectives might be technically impracticable). Before a final remediation objective is selected, a constraints analysis has to be carried out which shows if certain remediation objectives are generally practicable or not. The next step within the screening phase is to couple the generally viable remediation objectives with the most economically remediation approach. As a result, a short list of remediation approaches is obtained, including a plan that shows how each approach achieves the remediation objectives whereby different remediation technologies are used for that purpose.[86]

5.7.2 Step 2: Qualitative Analysis

The qualitative analysis is an assessment method which investigates the effects of the different remediation options (from the beginning to the end of the remediation measures) whereby certain categories are investigated. Which categories are investigated within the qualitative analysis varies depending on site specific circumstances; however the effects of the remediation options on human health and the environment should be considered in every qualitative analysis.[87]

Within this framework the qualitative analysis is divided into five major categories which also have certain subcategories. The five major categories that are used within this framework are:

- Human health and safety
- Environment
- Land use
- Stakeholder concern
- Option costs

Within the qualitative analysis, questions arise (as seen in the table below) - whereby the impacts before, during and after the remediation are investigated - for the remediation options that are generally viable for achieving the given remediation objectives. The questions can be answered with yes (Y), no (N) or if the answer of a question is not explicit this can be expressed with the use of a questions mark. Therefore, if a question is likely to be answered with yes, then a (Y?) is used, and if a question is likely to be answered with no, then a (N?) is used. Now the questions which arise from the subcategories are answered for the different remediation options either with a (Y), (Y?), (N), (N?) as it is shown in the next table. A qualitative analysis has been carried out for two remediation options as shown in the next table.[88]

Of course it is possible to apply other sets of questions within the qualitative analysis, too.

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[86] Cf. HARDISTY P., OZDEMIROGLU E. (2000), p.28 f.

[87] Cf. MINISTRY OF TRANSPORTATION (2006), p.30

[88] Cf. POSTLE M. et al. (1999), p.27 f.

Table 12: Qualitative Analysis[89]

	Before Remediation	During remediation		After remediation	
Category	Remediation Option:	1	2	1	2
Human health and safety					
Significant risk to site users?	N	Y	Y	N	N
Significant risks to public?	Y	Y	N?	N	N?
Significant numbers of site users exposed?	N	N	N	N	N
Significant number of public exposed?	Y	Y	N	N	N
Environment					
Impacts on quality of surface water?	N	N	N	N	N
Impacts on quantity of surface water?	N	N	N	N	N
Impacts on quality of groundwater?	N	N	N	N	N
Impacts on quantity of groundwater?	N	N	N	N	N
Impacts on local air quality?	Y	Y?	Y?	N	N?
Plant and animal numbers affected?	N	N	N	N	N
Designated sites impacted?	N	N	N	N	N
Land Use					
Site land value reduced?	Y	N	N	Y?	Y

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[89] Cf. POSTLE M. et al. (1999), p.34

Surrounded land value reduced?	N?	N	N	N?	Y?
Site land use restricted?	Y	Y	N	N	Y?
Surrounding land use restricted?	N?	N	N	N	N
Stakeholder concern					
Significant level of public interest?	Y	Y	Y	Y	N?
Lack of available information?	N	N	N	N	N
Total Option Costs [€]				150.000	250.000

After the questions have been answered, the total option costs of the remediation options need to be assessed. The total option costs consist of the costs of the different remediation options (whereby the net present value is calculated in order to make the costs of the different remediation options comparable) plus the compensation costs (for those who are affected by the contamination).After the qualitative analysis is completed, one remediation option might be clearly preferable, and if this is the case, there is no need to complete the next steps that are provided within this framework.[90]

5.7.3 Step 3: Cost Efficiency Analysis/Multi Criteria Analysis

During the qualitative analysis the impacts before, during and after remediation are identified for the investigated categories, however it does not provide information on the importance of the categories according to the final decision regarding which remediation option is ultimately chosen. The goal of a multi criteria analysis is to provide a system which makes it possible to compare and score the effects of the remediation options on the particular categories and subcategories which were investigated during the qualitative analysis. This is achieved by assigning scores to the investigated categories and subcategories.

A very important property of a MCA is that it relies on the subjective perspectives of the decision making team because the impacts that are investigated are subjectively assessed. One could argue that this is a limitation of MCA because it only reflects the views of decision makers; however this limitation can be overcome with a sensitivity analysis whereby other scores can be applied to categories and subcategories in order to reflect views of other stakeholders.[91]

When the multi criteria analysis is finished, the total scores of the remediation options are linked with the costs of these options. As a result, a ranking is obtained which reflects the cost effectiveness of the investigated remediation options. An example of how this scoring process works is shown exemplarily for the subcategory *impacts on local air quality*, from the category environment, for three remediation options. For the first remediation option,

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[90] Cf. POSTLE M. et al. (1999), p.35 f.

[91] Cf. DEPARTMENT FOR COMMUNITIES AND LOCAL GOVERNMENT (2009), p.20

volatile organic emissions are generated during the execution of the remediation measures, whereas for the second remediation option only half of the emissions are generated and for the third option there are no emissions at all. In such a case, the first option would generate a score (concerning the subcategory *"impacts of local air quality"*) of -100, the second a score of -50 and the third a score of 0. During remediation the scores run from -100 to 0; where -100 is given to the remediation option with the worst impact and 0 to an option with no impact. After remediation the scores run from 0 to +100; where 0 is given to the option with no benefit and +100 is given to the option with the greatest benefit. It is also possible to apply an uncertainty margin e.g. +/- 10. These uncertainties are important for the final assessment of the remediation options, where a sensitivity analysis can be applied. How the sensitivity analysis works in detail is explained in the last step of the framework. The next table gives an example of the scoring process (for the subcategory *impacts on local air quality,* from the category environment) for three different remediation options.

Table 2: Example of scoring process

Criteria	Options	Score		Uncertainty (+/-)	
Impacts on local air quality		During	After	During	After
	Option 1	-100	+50	10	0
	Option 2	-50	+75	10	0
	Option 3	0	+100	0	0

Now all the subcategories and the associated uncertainties have to be scored for "during and after the remediation process" for the investigated options.[92]

After the scoring process of the subcategories has been finished, the values of all subcategories within one category are added. Then the five categories have to be weighted according to their relative importance for the overall decision which remediation options to choose. The weighting of the categories is different depending on individual site conditions. A weight of 1 is applied to the most important category and depending on the relative importance of the other categories a value between 0 and 1 is applied. Different sets of weights can also be applied for "during remediation" and "after remediation". Now the weight is multiplied with the results of the scoring process for the particular categories, the categories are than added and a total weighted score is obtained for all the investigated remediation options. The scoring and weighting process for three categories of one remediation option is provided in the following example (the same procedure needs to be carried out for all other investigated options):

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[92] Cf. POSTLE M. et al. (1999), p.46 ff.

Table 3: Example of scoring and weighting process

Option 1			
	Human Health and Safety	Environment	Stakeholder concern
During remediation	-150	-80	-24
After remediation	+110	+100	+200
Total score	-40	+20	+176
Weight applied	1.0	0.1	0.5
Score	-40	+2	+88
Total Score	**+50**		

When the total score of at least one of the investigated remediation options is positive, then all option scores are divided by their net present value. As a result, the cost effectiveness of the remediation options is obtained. The higher the calculated value above zero, the better the cost effectiveness of the investigated option. When the total scores of all investigated remediation options are negative, then the total scores have to be multiplied by the net present value costs of the associated remediation options. The option with the highest cost-effectiveness is that option which is closest to zero. Only the net present value costs of the different remediation options have been considered during this step of the framework, and at this stage a cost benefit analysis should be carried out which gives a more accurate picture of the economic considerations of the investigated remediation options. [93]

5.7.4 Step 4: Cost Benefit Analysis (CBA)

It has to be noted that it is generally possible to apply monetary values to all of the subcategories (which were investigated within this framework) by applying a range of different valuation techniques such as the willingness to pay or the willingness to accept approach.

The willingness to pay approach investigates how much money potential gainers would pay for benefits obtained from a potential remediation option. On the other hand, the willingness to accept approach investigates how much compensation potential losers would receive for potential losses. If the benefits exceed the losses, a project would then be generally classified as being desirable. However, the willingness to pay and willingness to accept approach are probably more suitable for remediation projects that are carried out from the government and not for projects that are privately managed, because these approaches focus more on affected stakeholders' views and not on problem holders' views.[94]

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[93] Cf. POSTLE M. et al. (1999), p.72 ff.

[94] Cf. DEPARTMENT FOR COMMUNITIES AND LOCAL GOVERNMENT (2009), p.15 f.

This is the reason why the above named valuation techniques have not been applied within this framework and only subcategories which can be easily valued in monetary terms are assessed.

The following impacts are monetarily assessed within this framework and will be subsequently explained: the impacts of the remediation options on *site land value*, the *land value of property that is neighbouring the site*, and *the quantity and quality of water resources* affected by the contamination. Concerning the site land value and the land value of property that is neighbouring the site it can be said that the value of the contaminated property and the neighbouring properties will be higher after the remediation measures are finished. The land value (after the remediation measures are finished) depends on the remediation option that has been chosen, because it determines for which purposes the property can be used. Concerning the quantity and the quality of the groundwater, it has to be noted that the contamination can, depending on the site specific hydro geological conditions, migrate off site. When there is potential for the contamination to migrate off site the effects on other water resources has to be evaluated. The benefits of remediation are then the future damage costs that are avoided. Therefore, the costs and benefits concerning the change in land value and the avoided damage costs (if it is probable that contamination migrates off site) have to be assessed for the different remediation options. The costs of the remediation options, plus the additional value of the property minus the damage costs avoided, need to be calculated for the remediation options. The total score of the remediation options (which was assessed in the MCA) then needs to be recalculated without the above named monetary valued issues. The cost effectiveness of the remediation options can then be calculated again by dividing the total weighted score by the net present value costs of the remediation methods, plus the additional value of the property minus the avoided damage costs. Then the remediation options can be ranked according to their cost effectiveness, whereby the higher the value of the cost effectiveness is above zero the better the rank. [95]

Table 13: Cost effectiveness

Option	Total Score	NPV Costs + additional land value – avoided damage costs (€)	Cost effectiveness	Rank
Option 1	+80	200.000	4	1
Option 2	+50	300.000	1.6	2

5.7.5 Step 5: Sensitivity analysis

The last step (sensitivity analysis) within this framework is now to determine the importance of the uncertainties that have been applied in step three (MCA) of the framework, and to see if such uncertainties change the rank order of the remediation options. These uncertainties can be used to recalculate the scores in two different ways: The first possibility is to assume that these subcategory values (where uncertainties have been applied) are

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[95] Cf. POSTLE M. et al. (1999), p.81

underestimated; in this case one has to add the uncertainty of the subcategories to the total score in order to obtain the revised score. The second possibility is to assume that these subcategory values (where uncertainties have been applied) are overestimated; in this case one has to subtract the uncertainty of the subcategories from the total score in order to obtain the revised score. Then the revised scores of the different remediation options are recalculated, once with the underestimated subcategories and once with the overestimated subcategories. Then one has to look if the revised scores change the rankings of the remediation options. When the ranking of the remediation options change it may be necessary to give additional thought to the implications of the change. Another application of the sensitivity analysis is to change the weights that have been applied for the categories. Different sets of weights can be applied to reflect the views of concerned stakeholders.[96]

Also for other issues, such as the discount rate (that is used for the calculation of the net present value) or the scheduled duration of the decontamination options, a sensitivity analysis can be applied in order to see if changes in these issues change the ranking of the remediation options.[97]

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[96] Cf. POSTLE M. et al. (1999), p.104 ff.

[97] Cf. HARDISTY P., OZDEMIROGLU E. (2004), p.245 f.

6 Legislation

One of the goals of this thesis was to provide a review on the legislation that deals with contaminated sites in Europe and in Austria. The main problem which is associated when investigating and comparing the current legislation within Europe is that the legislation differs significantly from country to country. This is the reason why it is difficult to find uniform decision criteria by which legislation can be compared within European countries. This was the reason why I decided to treat European legislation, concerning the handling of contaminated sites, on the basis of the Heracles study. The Heracles study has the advantage that it provides uniform decision criteria for the comparison of European legislation (such as the receptors that are protected from corresponding laws, human health risk assessment or ecological risk assessment). Furthermore, the Heracles study also analysed the basis on which screening values were applied and the major changes which can be expected in European legislation.

Concerning the legislative situation in Austria, the most important laws and ÖNORMs which deal with the handling of contaminated sites have been investigated.

6.1 Heracles Study

An overview on the findings of the Heracles Study is provided in the following chapter. Fifteen European countries participated in the study (Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Italy, Lithuania, Poland, Slovak Republic, Spain, Sweden, The Netherlands and the United Kingdom). The study analyses the basis of the screening values that are used in the above named countries. It focussed on soil contamination, but it also investigated the relation between soil and groundwater screening values. The screening values that are adopted within the participating countries can said to be variable in many aspects because of scientific and political reasons.[98]

In most of the participating countries, the screening values are accommodated from laws that were especially designed for the handling of contaminated sites, in some countries the screening values are accommodated from soil and groundwater protection laws and only in a few countries the screening values are found within waste management laws. So, the legal basis concerning the screening values on which remediation measuers are carried out can said to be very variable within the participating countries. Generally, it can be said that there is a movement to apply soil screening values together with risk assessment. How risk assessment is properly carried out is discussed in the fourth chapter of this thesis. Eleven countries have developed their own risk assessment models for the deviation of soil screening values whereas other participating countries, such as Austria, adopted the screening values from other countries. The scientific basis for the development of risk assessment models with the associated screening values are: EC technical Guidance Document on risk assessment, US-EPA and US-ASTM guidance, methods that were developed in the Neth-

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[98] Cf. CARLON C. (2007), p.2 f.

erlands and for countries that have been part of the Soviet Union: methods and values that have been developed in the Ex- Soviet Union.[99]

In the following, the main differences and similarities concerning the receptors that are being protected by the corresponding laws are investigated for the countries that participated in the study.

Protected receptors

Every country considers a different set of receptors that need to be protected. For the manifold receptors there are distant sets of soil screening values that are applied. The next figure provides an overview of the protected receptors within participating countries. Already in use (AIU) signifies that methods and values concerning the receptor are already in use, under evaluation (UE) signifies that there is a plan under evaluation which might lead to the adoption of soil screening values for the affected receptor. When the cells are blank this signifies that the receptor is simply not considered and that there is no effort made to change the current situation.

Table 14: Protected Receptors[100]

	Human health	Terrestrial Ecosystem	Groundwater	Surface Water
Austria	AIU	AIU	AIU	AIU
Walloon (BE)	AIU	UE	UE	
Flanders (BE)	AIU	UE		
Czech Republic	AIU	UE		
Denmark	AIU	UE	AIU	
Germany	AIU	AIU	AIU	
Finland	AIU	AIU		
Italy	AIU		AIU	
Lithuania	AIU			
Netherlands	AIU	AIU		
Poland	AIU		AIU	

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[99] Cf. CARLON C. (2007), p.26 f.

[100] Cf. CARLON C. (2007), p.29

Spain	AIU	AIU		AIU
Sweden	AIU	UE	AIU	AIU
United Kingdom	AIU	UE		

The above figure shows that the only receptor (for which soil screening values are applied in all of the participating countries) is human health, whereas there are many differences concerning the involvement or the expulsion of other receptors. Of course the involvement or the expulsion of the receptors significantly affects the resulting soil screening values.[101]

6.1.1 Human health risk assessment

The goal of a human health risk assessment is to assess if the contaminants (that are present in the subsurface) can pose a potential risk to human health. How risk assessment is carried out is discussed in subchapter 3.1 (risk management) within this thesis. Concerning human health, a risk may exist when the contaminants come into physical contact with the skin, by human intake (eating and drinking) or by inhalation of contaminants that are present as vapours.[102]

As it was noted above, human health based soil screening values exist in all the participating countries, and in most countries, there are even efforts to extend the existing values. In almost all of the participating countries, the soil screening values (which are implemented for human health) depend on the kind of land use. Different soil screening values are applied for certain land uses. In a few countries (Netherlands, Denmark and Slovak Republic) generic soil screening values are applied for human health. This means, that the soil screening values are not applied depending on land use, but on the basis of site specific factors.[103]

The kinds of land use for which different soil screening values are applied are summarised in the next figure.

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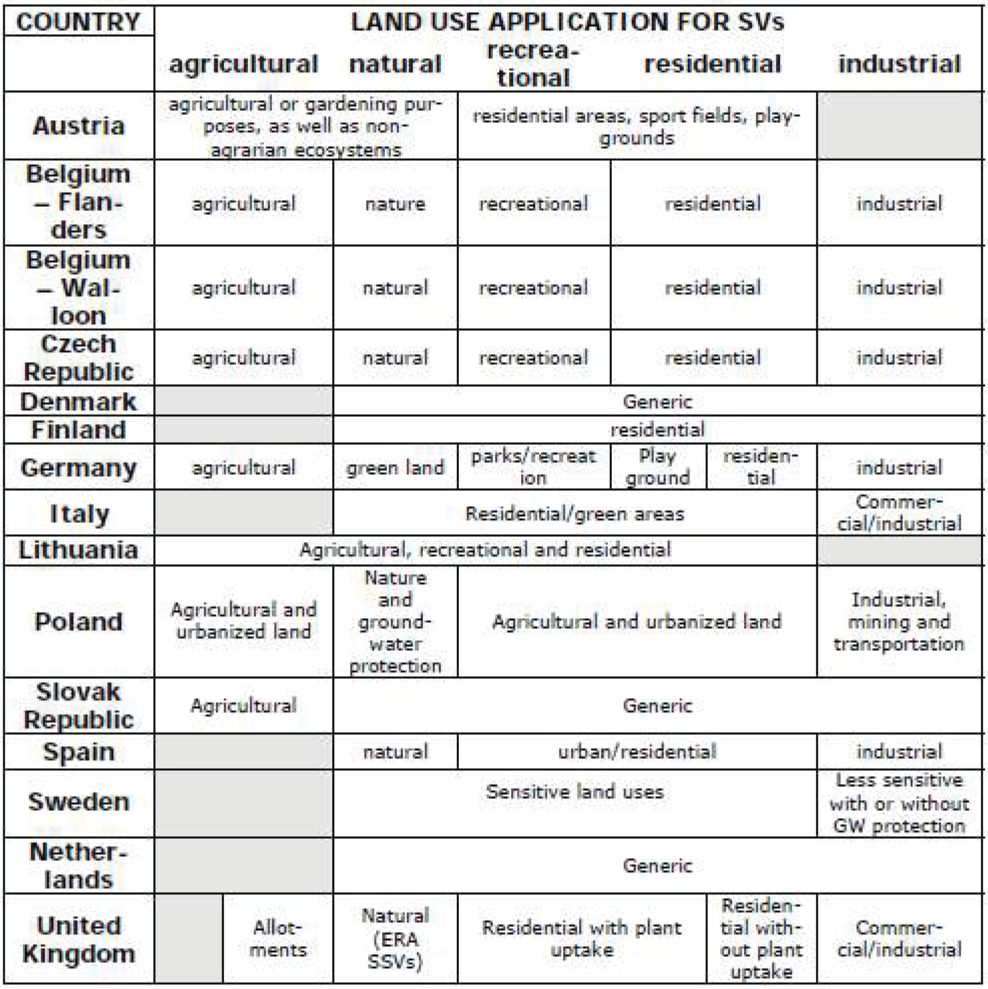
[101] Cf. CARLON C. (2007), p.28 f

[102] Cf. CONTAMINTED SITES REMEDIATION PROGRAM (2000), p.44

[103] Cf. CARLON C. (2007), p.34

Table 15: Land use applications of soil screening values[104]



COUNTRY	LAND USE APPLICATION FOR SVs				
	agricultural	natural	recreational	residential	industrial
Austria	agricultural or gardening purposes, as well as non-agrarian ecosystems		residential areas, sport fields, playgrounds		
Belgium – Flanders	agricultural	nature	recreational	residential	industrial
Belgium – Walloon	agricultural	natural	recreational	residential	industrial
Czech Republic	agricultural	natural	recreational	residential	industrial
Denmark		Generic			
Finland		residential			
Germany	agricultural	green land	parks/recreation	Play ground residential	industrial
Italy		Residential/green areas			Commercial/industrial
Lithuania	Agricultural, recreational and residential				
Poland	Agricultural and urbanized land	Nature and groundwater protection	Agricultural and urbanized land		Industrial, mining and transportation
Slovak Republic	Agricultural	Generic			
Spain		natural	urban/residential		industrial
Sweden		Sensitive land uses			Less sensitive with or without GW protection
Netherlands		Generic			
United Kingdom	Allotments	Natural (ERA SSVs)	Residential with plant uptake	Residential without plant uptake	Commercial/industrial

6.1.2 Ecological risk assessment

Ecological risk assessment is used to investigate if the contaminants, which are present in the subsurface, pose a risk to the surrounding environment. It is also used to show pathways of how potential receptors can come into contact with contaminants. The goals of ecological risk assessment are good comparable with the goals of human health risk assessment, with the difference that other receptors (plants and animals) are considered. Essentially it can be said that ecological risk assessment is used to assess if remediation measures need to be carried out for environment protection.[105]

The ecological receptors which were considered in the derivation of ecological soil screening values (in the investigated EU countries) are shown in the next table. C stands for considered and NC stands for not considered. Furthermore, different soil screening values need to be applied for every ecological receptor.

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[104] Source: CARLON C. (2007), p. 35

[105] Cf. EPA (1997), p.3

Table 16: Ecological receptors considered in the derivation of SSV in the participating EU countries[106]

	Microbiological Processes	Soil fauna	Plants	Above soil ecosystem	Aquatic ecosystem
Austria	NC	NC	C	NC	NC
Walloon (BE)	C	C	C	NC	NC
Flanders (BE)	C	C	C	NC	NC
Czech Republic	C	NC	C	NC	NC
Germany	C	C	C	C	NC
Spain	C	C	C	C	C
Finland	C	C	C	C	NC
Netherlands	C	C	C	C	NC
Sweden	C	C	C	C	C
United Kingdom	C	C	C	C	NC

In all participating countries, with the exception of Austria and the Czech Republic, microbiological processes and the soil fauna are considered in the derivation of the ecological soil screening values. Generally it can be noted that there is a high variability which ecological receptors are considered or not considered. The main reasons for the high variability are political decisions that are supported by scientific knowledge.[107]

6.1.3 Relation between soil and groundwater screening values

All the countries which participated in the study provide screening values for contaminated groundwater. In most countries the groundwater screening values are based on toxicological standards for drinking water use (which have been provided from the WHO). The main disadvantage of the WHO standards is that they do not take into account if contaminated aquifers will be adopted for drinking water or a comparable use in the future. This means

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[106] Cf. CARLON C. (2007), p.49

[107] Cf. CARLON C. (2007), p.48 f

that a remediation to drinking water standards might not be necessary for aquifers that are not going to be used in the future, and a remediation to a lesser extent might be appropriate for these aquifers. Some countries consider this fact and take into account regional contamination backgrounds. The main weaknesses of the groundwater screening values that were applied in participating countries, apart from the use of drinking water criteria from WHO, appear to be the following: Eco-toxicological criteria which show the impact of the contamination on aquatic and terrestrial ecosystems are not applied (with the exception of Germany, Denmark and the Netherlands). There is also a missing harmonisation of groundwater screening values with the soil screening values, and a missing distinction between sensitive use (e.g. drinking water) and non-sensitive use (no planned use in the future) for the contaminated aquifer, in many of the investigated countries. Nevertheless, a new European legislation (formulated by the European Commission), where the above mentioned weaknesses are going to be fixed, will be set in the future. A complementary groundwater directive is going to be implemented which supports the already existing water framework directive. The complementary groundwater directive governs criteria for the assessment of the chemical status of the groundwater. Also pollutant thresholds need to be assessed for aquifers that might be affected from contamination. [108]

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[108] Cf. CARLON C. (2007), p.74 f.

6.2 Austrian Legislation

The most important laws in Austria concerning the remediation of contaminated sites are the following:

- The **Water Act** (Wasserrechtsgesetz) from 1959 is based on the precautionary principle. The overall intent of the law is to maintain the groundwater in its natural condition. The groundwater also has to fulfil drinking water requirements. 99% of the Austrian drinking water is groundwater, so the protection of groundwater is extremely important.[109]
- The **Federal Act on Clean-up of Contaminated Sites** (Altlastensanierungsgesetz, ALSAG) from 1989 was designed to obtain money that can be used for financing remediation measures. In practice, this means that ALSAG charges have to be paid for every tonne of contaminated material that is brought to a disposal facility. With the money that is gained, the state is able to finance other remediation projects. It has to be noted that the law does not define any criteria which can be used as a guideline to carry out risk assessment or procedures for the deviation of screening values.
- The **Waste Management Law** (Abfallwirtschaftsgesetz) from 2002 is executed when the remediation of contaminated land is in the public interest.
- **Disposal Ordinance** (Deponieverordnung) from 2008 contains different threshold values for contaminated material that is brought to disposal facilities.[110]

A law which is particularly designed for the purpose of remediation of contaminated land does not exist in Austria. The remediation of contaminated land is carried out mainly on the basis of the Water Act, and to a lesser extent, on the basis of the Waste Management Law. Previously, remediation measures were also carried out on the basis of the Trade, Commerce and Industrial Regulation Act (Gewerbeordnung), however this Act is not applied anymore. It has to be noted that the Water Act was not originally designed for the management of contaminated land and does not provide target values which have to be achieved for successfully remediating a contaminated site. In practice, target values are taken from the ÖNORMs.[111]

The Austrian Standard Institute published a sequence of guidelines which provide valuable information for the management of contaminated sites (ÖNORM S 2085 – 2090). An overview on the most important issues concerning the handling of the ÖNORMs for contaminated sites is provided in the following.

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[109] Cf. CARLON C. (2007), p. 129

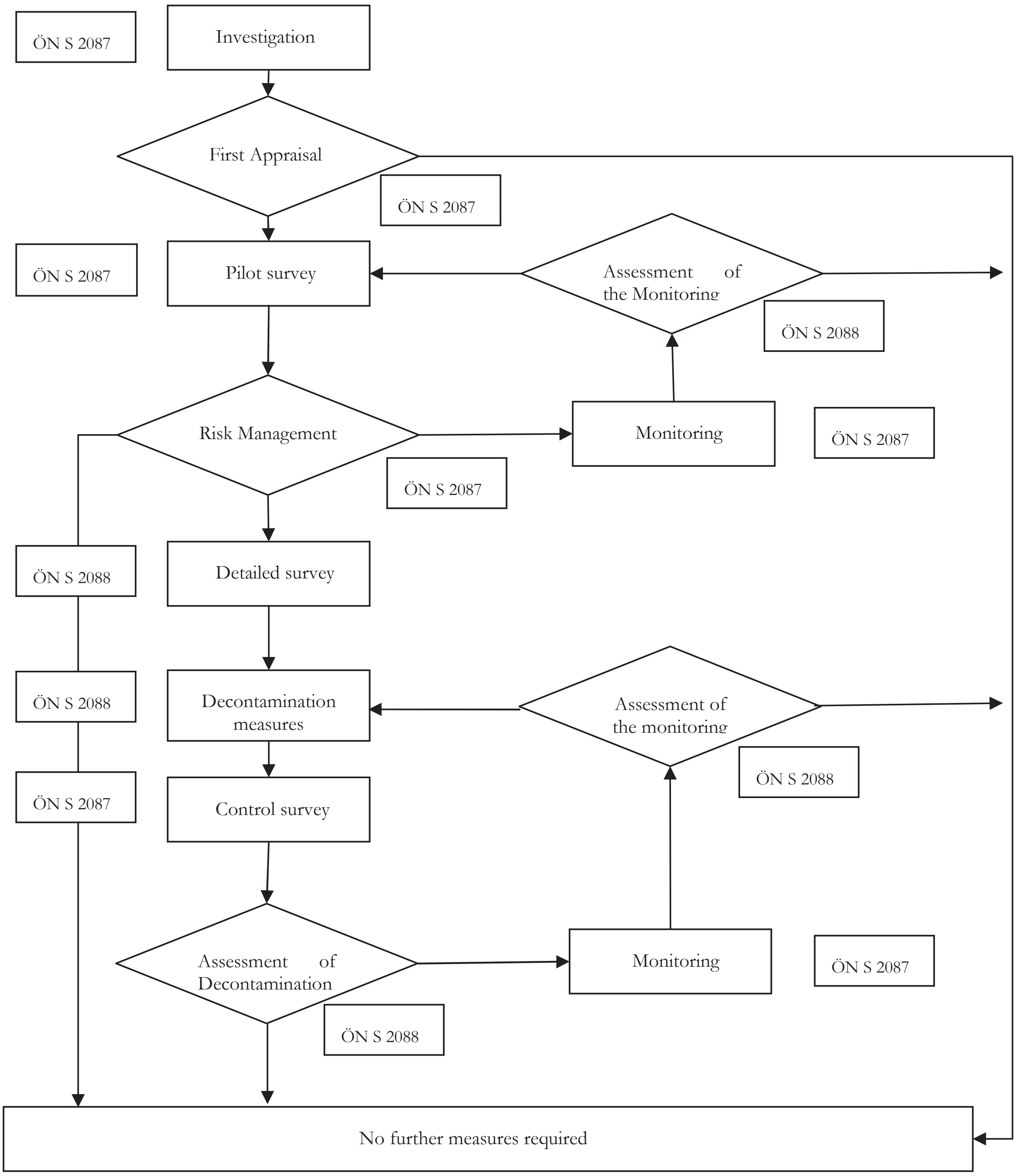
[110] Cf. ANHANG ZUR DEPONIEVERORDUNG, BGBL. II

[111] Cf. SKALA C. et al. (2008), p.166 f.

6.2.1 ÖNORM S 2085 from 1999: contaminated sites – course of actions for treatment of waste deposits and industrial sites

The ÖNORM S 2085 provides a flow diagram illustrating a systematic approach for the handling of contaminated sites. The flow chart and a short description of the steps illustrated in the flow chart is provided in the following:

Table 17: Flowchart of decontamination measures[112]



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[112] Cf. ÖENORM S 2085 (1998), p.3

Short Description of the procedural steps:

Within the investigation, all the information which concerns the potentially contaminated site is collected. With the help of the obtained information, it is then assessed if further investigations need to be carried. If it is decided that a further investigation is necessary, a pilot study is undertaken. The aim of the pilot study is to obtain information on the site's risk potential. There are two different types of analysis which can be undertaken; one is for the identification of contaminants and the other for the investigation of the potentially contaminated site and its surroundings. Examples of methods that are used for this purpose include hydro geological investigations, water analysis, and solid analysis. These methods are explained in detail in ÖN S 2087. The results of the pilot study are used as a basis for the planning of the decontamination measures and subsequently for the assessment of the effectiveness of the remediation measures. After the pilot study, a risk assessment that particularly concerns soil and groundwater screening values (ÖNORM S 2088/1 and 2) is carried out. The results of the risk assessment determine: (a) if decontamination measures need to be undertaken, (b) if the site needs monitoring or (c) no further measures are necessary. If decontamination measures have to be performed a more detailed survey (in comparison to the previous investigation) needs to be made. During the ongoing decontamination measures the progress of the remediation measures should be documented and attended controls need to be undertaken. The decontamination measures are successfully completed if the remediation goals (set by the Umweltbundesamt) are reached. [113]

6.2.2 ÖNORM S 2088 – 2 from 2000, contaminated sites – risk assessment for polluted soil concerning impacts on surface environment

The goal of the ÖN S 2088-2 is to provide certain criteria which form the basis for the assessment of screening values for the remediation of contaminated soils. After the remediation measures are finished, one of the following remediation goals needs to be achieved: [114]

- Restoring or preserving the natural state of the soil.
- Preserving or establishing a state that allows a sustainable multi-functional use of the soil.
- Preserving or establishing an environmental state allowing a limited use and prevention of further discharges of hazardous substances to the soil.

It is the aim of the ON S 2088-2 is to define common criteria for soil contamination and the possible effects of the contamination on humans and plants. The soil screening values that are applied in the ON S2088-2 are used to assess investigation results and to define the target values for remediation projects.[115]

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[113] Cf. ÖENORM S 2085 (1998), p.4 ff.

[114] Cf. ÖENORM S 2088 – 2 (2000), p.5

[115] Cf. REVIEW OF DECISION SUPPORT TOOLS (2002), p. 119

The soil screening values of the ÖNORM S 2088-2 have been established by a working group from the Austrian Standard Institute. The working group investigated the soil screening values of fifteen countries and these investigations formed the basis for the development of soil screening values applied in the ÖNORM S- 2088-2.[116]

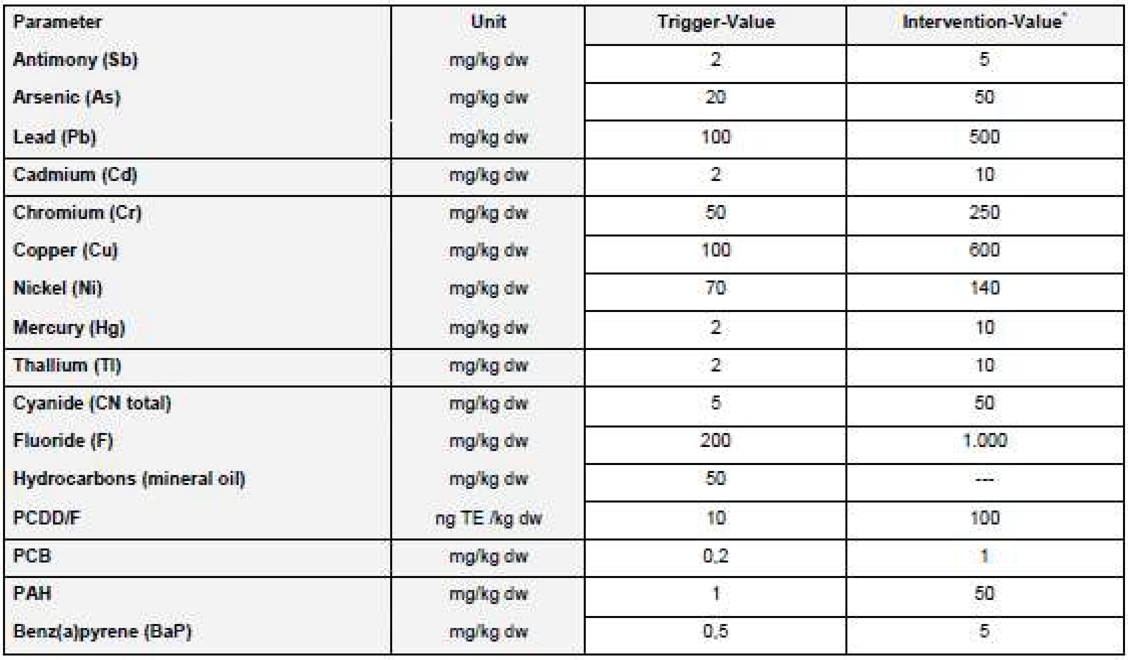
Generally, the soil screening values (defined in the ÖN S 2088-2) relate to specific soil functions. There are three different soil functions defined in the ÖNORM S 2088-2:[117]

- Soil in its function for humans
- Soil in its function for production (agricultural use)
- Other uses – Soil as a filter and as a buffer within ecosystems (non-agrarian use)

Ad) Soil in its function for humans:

The next table sets out guideline values defined for contaminated top soils (0-10cm) such as residential areas where an oral intake from contaminated soil can occur.

Table 18: Guideline values for residential areas[118]



Parameter	Unit	Trigger-Value	Intervention-Value*
Antimony (Sb)	mg/kg dw	2	5
Arsenic (As)	mg/kg dw	20	50
Lead (Pb)	mg/kg dw	100	500
Cadmium (Cd)	mg/kg dw	2	10
Chromium (Cr)	mg/kg dw	50	250
Copper (Cu)	mg/kg dw	100	600
Nickel (Ni)	mg/kg dw	70	140
Mercury (Hg)	mg/kg dw	2	10
Thallium (Tl)	mg/kg dw	2	10
Cyanide (CN total)	mg/kg dw	5	50
Fluoride (F)	mg/kg dw	200	1.000
Hydrocarbons (mineral oil)	mg/kg dw	50	---
PCDD/F	ng TE /kg dw	10	100
PCB	mg/kg dw	0,2	1
PAH	mg/kg dw	1	50
Benz(a)pyrene (BaP)	mg/kg dw	0,5	5

If the measured values are higher than trigger values then further investigations or monitoring needs to be carried out. If the values are higher than intervention values remediation measures need to be carried out.

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[116] Cf. CARLON C. (2007), p. 128
[117] Cf. ÖENORM S 2088 – 2: (2000), p. 11
[118] Source: CARLON C. (2007), p. 246

Ad) Soil in its function for agricultural use and non-agrarian use

The next table sets out guideline values defined for contaminated top soils (0-20cm) which have an agricultural or non-agrarian function.

Table 19: Guideline values for agricultural and non-agrarian ecosystem[119]

Parameter	Unit	Trigger-Value
Antimony (Sb)	mg/kg dw	2
Arsenic (As)	mg/kg dw	20
Lead (Pb)	mg/kg dw	100
Cadmium (Cd)	mg/kg dw	1
Chromium (Cr)	mg/kg dw	100
Copper (Cu)	mg/kg dw	100
Nickel (Ni)	mg/kg dw	60
Mercury (Hg)	mg/kg dw	1
Thallium (Tl)	mg/kg dw	1
Vanadium (V)	mg/kg dw	50
Zinc (Zn)	mg/kg dw	300
Fluoride (F total)	mg/kg dw	200
Cyanide (CN total)	mg/kg dw	5
Hydrocarbons (mineral oil)	mg/kg dw	200
PCDD/F	ng TE /kg dw	10
PCB	mg/kg dw	0,3
PAH	mg/kg dw	1

Only trigger values (and no intervention values) are provided for soil functions which consist of an agricultural or non-agrarian use. When trigger values are exceeded further investigations, which determine if remediation measures are necessary, need to be carried out.

Practical weaknesses of ÖN S 2088-2

Although the ÖNORM S 2088-2 has been established in a very pragmatic way, the main problem is that risk assessment procedures and applied screening values are not legally obligatory. Furthermore, there are no efforts made to establish risk assessment procedures or screening values that are legally binding. Another problem is that risk assessment procedures concerning contaminated soils have not been executed very often, and therefore, there is little knowledge concerning practical weaknesses.[120]

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[119] Source: CARLON C. (2007), p. 246

[120] Cf. CARLON C. (2007), p. 128 f.

6.2.3 ÖNORM S 2088 – 1 from 2004, contaminated sites – risk assessment concerning the pollution of groundwater which is to be safeguarded

The goal of the ÖN S-2088-1 is to provide certain criteria that form the basis for the assessment of groundwater screening values for the remediation of contaminated aquifers. The criteria that are used for this purpose generally refer to WHO guidelines (1993) for drinking water quality. The groundwater intervention values have been equally set to drinking water standards, and trigger values have been established at 60 % of the drinking water standards. The groundwater screening values have been established without relation to soil screening values. [121]

Once remediation measures have been completed, one of the following remediation goals needs to be achieved: [122]

- Restoring or preserving the natural state of the groundwater
- Preserving or establishing a state that allows a sustainable multi-functional use of the groundwater
- Preserving or establishing an environmental state allowing a limited use and prevention of further discharges of hazardous substances to the groundwater.

The fixing of the remediation goals is carried out while considering:[123]

- the kind, mobility and age of the petroleum contamination
- the results of the groundwater analysis
- the estimation of further development of the site (same use, change of use)
- analysis of the hydrological, geological and hydro-geological investigations

Concerning mobility (viscosity, water solubility, volatility) mineral oil can be divided into different sections:[124]

- High mobility (boiling range from 30°C – 180°C): Gasoline (C_5 – C_9) and solvents
- Medium mobility (boiling range from 180°C – 300°C): Diesel (C_{10} – C_{21}), Kerosene (C_{10} – C_{21}), heating oil extra light (C_9 – C_{23})
- Small Mobility (boiling range from 300°C): lubricants, hydraulic oil (Alkenes > C_{17})
- Very small mobility: heating oil heavy

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[121] Cf. CARLON C. (2007), p. 130

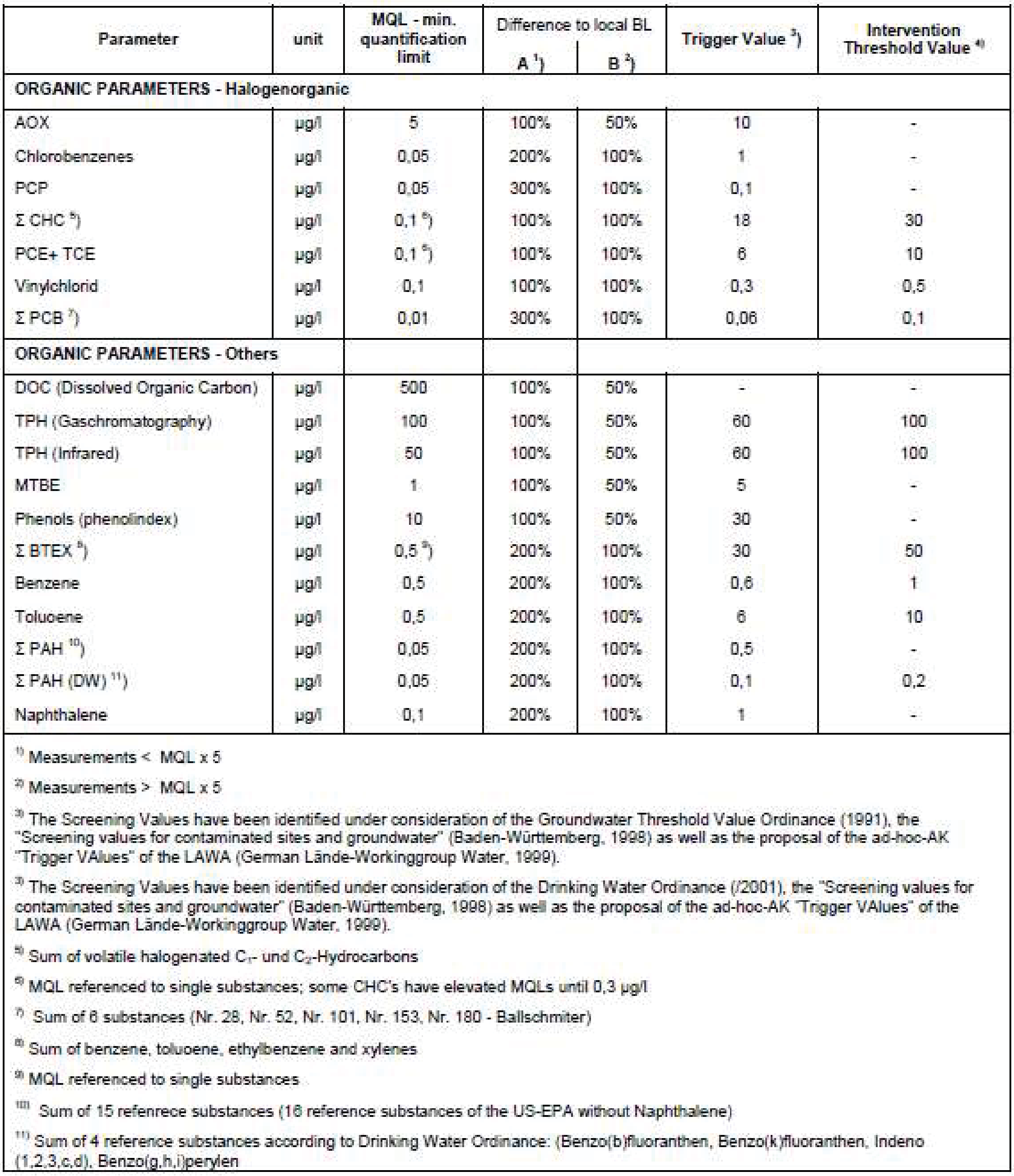
[122] Cf. ÖENORM S 2088 – 1 (2004), p. 6

[123] Cf. ÖENORM S 2088 – 1 (2004), p. 11

[124] Cf. ÖENORM S 2088 – 1 (2004), p. 13

Certain parameters need to be checked within the groundwater depending on the mobility of the mineral oil. Generally, the fixing of remediation goals depends on site specific circumstances. The following values can be used as a starting point for evaluating investigation results or can be used to define target values for remediation projects.[125]

Table 20: Trigger and intervention values for groundwater[126]



Parameter	unit	MQL - min. quantification limit	Difference to local BL		Trigger Value 3)	Intervention Threshold Value 4)
			A 1)	B 2)		
ORGANIC PARAMETERS - Halogenorganic						
AOX	µg/l	5	100%	50%	10	-
Chlorobenzenes	µg/l	0,05	200%	100%	1	-
PCP	µg/l	0,05	300%	100%	0,1	-
Σ CHC 5)	µg/l	0,1 6)	100%	100%	18	30
PCE+ TCE	µg/l	0,1 6)	100%	100%	6	10
Vinylchlorid	µg/l	0,1	100%	100%	0,3	0,5
Σ PCB 7)	µg/l	0,01	300%	100%	0,06	0,1
ORGANIC PARAMETERS - Others						
DOC (Dissolved Organic Carbon)	µg/l	500	100%	50%	-	-
TPH (Gaschromatography)	µg/l	100	100%	50%	60	100
TPH (Infrared)	µg/l	50	100%	50%	60	100
MTBE	µg/l	1	100%	50%	5	-
Phenols (phenolindex)	µg/l	10	100%	50%	30	-
Σ BTEX 8)	µg/l	0,5 9)	200%	100%	30	50
Benzene	µg/l	0,5	200%	100%	0,6	1
Toluoene	µg/l	0,5	200%	100%	6	10
Σ PAH 10)	µg/l	0,05	200%	100%	0,5	-
Σ PAH (DW) 11)	µg/l	0,05	200%	100%	0,1	0,2
Naphthalene	µg/l	0,1	200%	100%	1	-

1) Measurements < MQL x 5

2) Measurements > MQL x 5

3) The Screening Values have been identified under consideration of the Groundwater Threshold Value Ordinance (1991), the "Screening values for contaminated sites and groundwater" (Baden-Württemberg, 1998) as well as the proposal of the ad-hoc-AK "Trigger VAlues" of the LAWA (German Lände-Workinggroup Water, 1999).

3) The Screening Values have been identified under consideration of the Drinking Water Ordinance (/2001), the "Screening values for contaminated sites and groundwater" (Baden-Württemberg, 1998) as well as the proposal of the ad-hoc-AK "Trigger VAlues" of the LAWA (German Lände-Workinggroup Water, 1999).

5) Sum of volatile halogenated C_1- und C_2-Hydrocarbons

6) MQL referenced to single substances; some CHC's have elevated MQLs until 0,3 µg/l

7) Sum of 6 substances (Nr. 28, Nr. 52, Nr. 101, Nr. 153, Nr. 180 - Ballschmiter)

8) Sum of benzene, toluoene, ethylbenzene and xylenes

9) MQL referenced to single substances

10) Sum of 15 refenrece substances (16 reference substances of the US-EPA without Naphthalene)

11) Sum of 4 reference substances according to Drinking Water Ordinance: (Benzo(b)fluoranthen, Benzo(k)fluoranthen, Indeno (1,2,3,c,d), Benzo(g,h,i)perylen

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[125] Cf. REVIEW OF DECISION SUPPORT TOOLS (2002), p.119

[126] Source: CARLON C. (2007), p. 248

Practical weaknesses

The main weakness of ÖN S 2088-1 is the same as for ÖN S 2088-2, i.e. risk assessment procedures and screening values are not legally obligatory. In addition, groundwater screening values are based on WHO guidelines for drinking water and do not consider eco-toxicological considerations and the influence of the contamination on terrestrial ecosystems or groundwater ecosystems.

6.2.4 Summary of Austrian Legislation concerning contaminated sites

By Austrian law, the following stakeholders have to be involved in the decision making process: legislative bodies, the polluter who is responsible for the contamination and the owner of the contaminated property. Generally there is no legal obligation to inform interested parties such as neighbours of the contaminated property, the interested public or environmental NGOs. Even though there is no legal obligation to inform these parties, in practise some kind of public acceptance is often needed for the execution of remediation measures such as the entering of neighbouring properties. That is the reason why interested parties are usually kept informed, or if necessary included in the decision making process. When risk assessment procedures are carried out, the ÖNORMs S2088-1/2 provide trigger and intervention values which govern the future course of action. Even though trigger and intervention values often provide the basis for the setting of remediation goals these values do not necessarily govern these goals, because the fixing of the remediation goals occurs under the consideration of site specific factors. That is the reason why it is generally possible that remediation goals are set some orders above the intervention values, which are defined in the corresponding ÖNORMs, even though there must be intensive investigations and feasibility studies to legitimate this approach. Another important issue is that, once a contamination is verified at a site, this can result in restrictions of the current land use. The decision if restrictions are applied on the current land use, lies in the responsibility of the nine Austrian states because this mainly depends on regional and local circumstances. Finally it has to be noted that the Federal Environmental Agency (Umweltbundesamt) is the responsible body for fixing and controlling remediation goals. The Agency is also responsible for the assessment of the success of remediation measures. [127]

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[127] Cf. REVIEW OF DECISION SUPPORT TOOLS (2002), p. 118 ff.

7 Economic comparison of remediation methods

The previous chapters in this thesis focused on an integrated observation on contaminated land management. These chapters are particularly useful in facilitating the choice of a particular remediation method for future remediation projects. This chapter focuses on economic considerations of already existing remediation projects that are currently being carried out by OMV.

7.1 Summary of the issues that are investigated in this chapter

The following questions will be answered in this summary:

- What is the starting base and what data was provided by OMV?
- What was done with the data that was provided?
- What tools where used in order to get to the intended results?
- Why were these investigations carried out?

7.1.1 What is the starting base and what data was provided by OMV?

There are nine insitu projects currently being carried out by OMV. The main goal of this thesis is to investigate which costs would have accumulated if excavation would have been chosen instead of the insitu option for the nine investigated projects. For that purpose the following data was provided by OMV:

- The data for the spatial extent of the contaminations and the scheduled duration of the remediation measures.
- The cost data of these projects, which consist of installation and operating costs, have also been included. The installation costs date from the year of the erection of the decontamination facility and are divided into different fractions. The operating costs date from the year 2007 and have been also divided into different fractions. The allocation of installation and operating costs (into different fractions) is of major importance in order to investigate the main cost causers of insitu projects.

Apart from the insitu cost data, data for the calculation of the excavation costs was also included. The data which is set out in Table 11 consists of:

- Minimum, most likely and maximum excavation costs
- Minimum, most likely and maximum disposal costs

- Cost data for planning, site supervision, construction site burden costs (these costs are calculated with 10 % of the overall costs that accumulate for excavation and disposal)

Also a discount rate of 5% was provided. The discount rate makes the comparison of remediation options which have a different time frame (such as it is the case with excavation and the insitu methods) possible.

Note: All the data which was obtained by OMV was provided by Ing. Rainer Novak and Dipl. Ing. Johan Siwcyk. The data concerning the excavation costs (table 11) has been provided by Ing. Rainer Novak and Dipl. Ing. Johan Siwcyk together. The discount rate was provided by Ing. Rainer Novak. All the other data has been provided by Dipl. Ing. Johan Siwcyk.

7.1.2 What was done with the data that was provided?

1. First of all a project description has been provided for all of the investigated projects. The nine investigated projects have letters which range from A to I. The names of the projects and the associated project letters are listed separately for internal use (for OMV only).

The nine projects have been divided into three subcategories:

- small contaminated volume (0 – 10.000 m³)
- average contaminated volume (10.000 m³)
- large contaminated volume (50.000 m³ - 500.000 m³)

The following course of action was chosen for the project descriptions:

At the beginning, the extent of the contamination (which consists of the following data: area fully contaminated, area partly contaminated, depth fully contaminated, height of the contamination plume, there from clean coverage and the scheduled duration of the decontamination measures) has been summed up in a table for the investigated projects. Then two tables which show the precise distribution of the installation and operating costs are illustrated. Afterwards the overall discounted insitu costs are summed up in a table. Thereafter the overall costs that would have accumulated if excavation would have been performed instead of the in-situ option are presented in a table. The table presents the results of the @risk simulation and sum up the minimum, most likely and maximum costs. At the end of the project description a graphical illustration depicts a comparison of the most likely excavation costs with the insitu costs.

2. Summary of excavation and insitu costs for investigated projects: For all of the investigated projects, the absolute costs and the costs per contaminated volume, which accumulate for the insitu and the excavation option, are illustrated in a table and in a figure.

3. One of the goals of this thesis was to find out at how much contaminated volume the insitu option is generally preferable over the excavation option, strictly from a cost point of view. For this purpose, this limit was calculated for three projects.

4. Finally, the main cost causers and their behavior (constant behavior or deviating behavior), within the installation and operating costs, for pump and treat and monitoring projects have been investigated.

7.1.3 What tools where used in order to get to the intended results?

Ad) Calculation of the excavation costs

A Program was developed for the simulation of excavation costs. The program is able to calculate excavation costs as long as the input parameters are known. An accurate explanation of the program, its working mode and the associated input parameters is provided in chapter 6.2 of the thesis. Within this thesis, the program has been used for the calculation of excavation costs for the nine investigated projects, but it can also be used for the calculation of excavation costs for future projects as long as the input parameters are known.

Ad) Economic comparison

An explanation of the economic appraisal that was used for the economic comparison of remediation methods is provided in the following. When you want to compare the insitu costs with the excavation costs that would have accumulated for the same remediation project, you have to consider the different time frames of the costs that accumulate. While insitu methods need a couple of years until remediation measures are finished, excavation is usually finished in less than a year. Therefore, the operating costs that accumulate for the duration of the insitu decontamination measuers have to be discounted, with the help of a discount rate, in order to obtain the present value of the insitu costs. Those costs can than be compared with the excavation costs (for excavation discounting is not necessary because excavation measures are finished in less than a year). The reason for the discounting is that money that is not spent in the present can be invested from the company on a rate that exceeds inflation.

The formula for the calculation of the NPV for a series of annual future operating costs is:

$$NPV_{OC} = \sum_{t=0}^{n} \frac{OC_t}{(1+i)^t}$$

Where:

NPV_{OC}…………………..Net Present Value in Euro at the base date

OC_t ……………………..Operating costs that accumulate each year from the base date to the scheduled end of the project

n ……………………….. Number of years to the scheduled end of the decontamination measures

i………………………….Discount rate in decimal form[128]

Note: The excavation costs are always compared with the present value of the insitu costs in the year of the erection of the decontamination facility. The year of the erection of the decontamination facilities, for the investigated projects, is provided in the project descriptions. The operating costs of all of the investigated projects date from the year 2007. The operating costs are assumed to behave constant over the scheduled duration of the decontamination measures. E.g. A insitu project was erected in the year 2005 and has a scheduled duration of 20 years. The operating costs that date from the year 2007 account for 100.000 €. It is then assumed that the operating costs account for 100.000 € every year, starting from the year 2005 ranging to the year 2025.

7.1.4 Why were these investigations carried out?

The main reasons why these investigations were carried out are listed in the following:

- For OMV it is of high interest to know how the excavation costs behave in relation to the insitu costs with increasing contaminated volume.
- To find out at how much contaminated volume insitu methods are, from a cost point of view, generally preferable over the excavation option.
- To know how much money has to be spent if the insitu methods fail to meet the objectives which are set from the responsible authorities, and as a result, excavation has to be performed instead.
- To design a program that is able to calculate excavation costs of future projects.
- To know (for pump and treat and monitoring projects) which specific fractions within the installation and operating costs appear to be the main cost causers.

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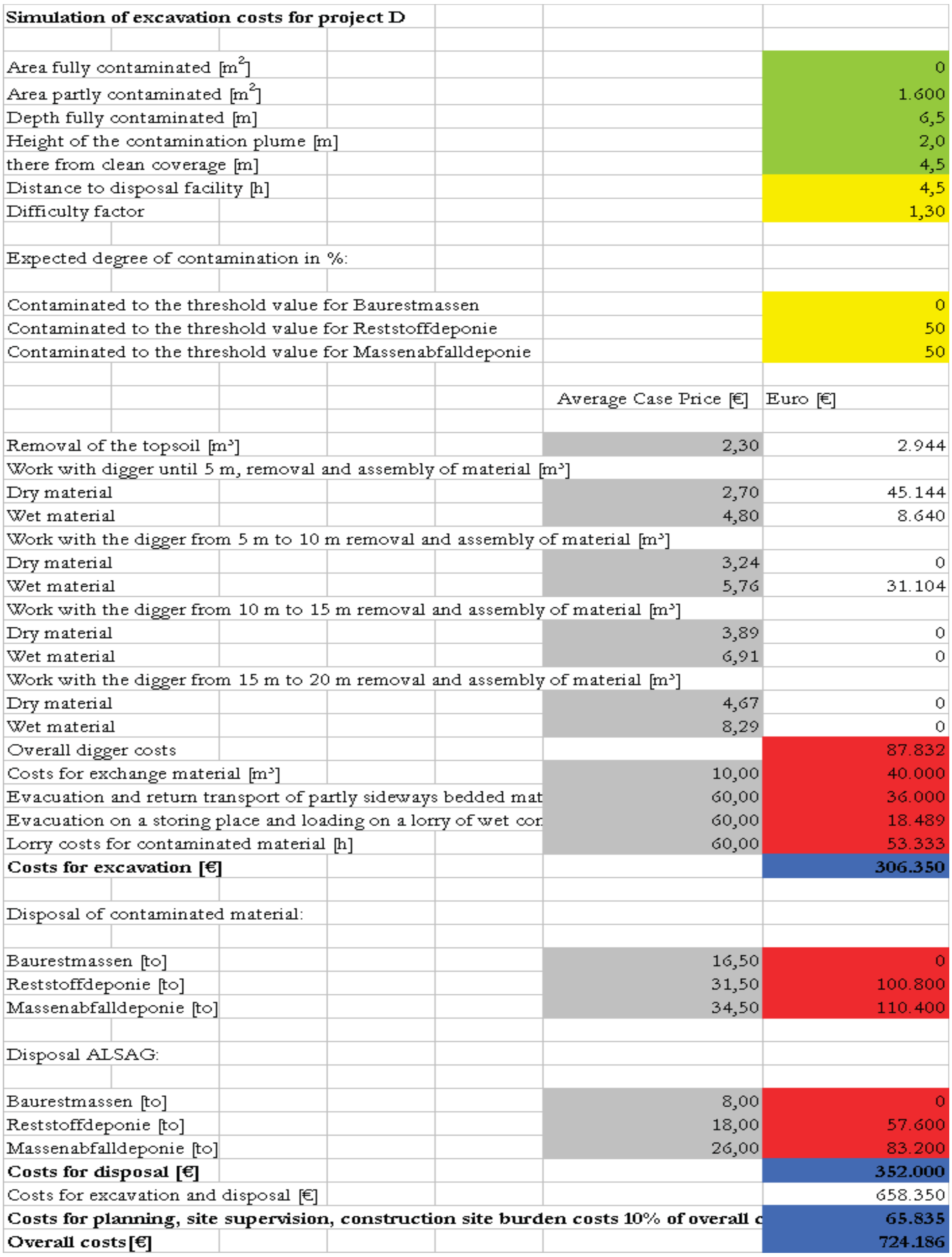
[128] SCHULZ L., WEBER S. (2003), p. 19

7.2 Explanation of the operating mode of the program that was used for the simulation of excavation costs

A program was prepared (in excel) which is capable of calculating the overall excavation costs. The program can be used in excel alone or it can be expanded with a software tool called @risk. Within this thesis the program was used in combination with @risk for calculating the minimum, most likely and maximum excavation costs for all of the investigated projects. The following excel screenshot shows the buildup of the calculation of the overall excavation costs exemplarily for project D.



Simulation of excavation costs for project D		
Area fully contaminated [m^2]		0
Area partly contaminated [m^2]		1.600
Depth fully contaminated [m]		6,5
Height of the contamination plume [m]		2,0
there from clean coverage [m]		4,5
Distance to disposal facility [h]		4,5
Difficulty factor		1,30
Expected degree of contamination in %:		
Contaminated to the threshold value for Baurestmassen		0
Contaminated to the threshold value for Reststoffdeponie		50
Contaminated to the threshold value for Massenabfalldeponie		50
	Average Case Price [€]	Euro [€]
Removal of the topsoil [m^3]	2,30	2.944
Work with digger until 5 m, removal and assembly of material [m^3]		
Dry material	2,70	45.144
Wet material	4,80	8.640
Work with the digger from 5 m to 10 m removal and assembly of material [m^3]		
Dry material	3,24	0
Wet material	5,76	31.104
Work with the digger from 10 m to 15 m removal and assembly of material [m^3]		
Dry material	3,89	0
Wet material	6,91	0
Work with the digger from 15 m to 20 m removal and assembly of material [m^3]		
Dry material	4,67	0
Wet material	8,29	0
Overall digger costs		87.832
Costs for exchange material [m^3]	10,00	40.000
Evacuation and return transport of partly sideways bedded mat	60,00	36.000
Evacuation on a storing place and loading on a lorry of wet cor	60,00	18.489
Lorry costs for contaminated material [h]	60,00	53.333
Costs for excavation [€]		**306.350**
Disposal of contaminated material:		
Baurestmassen [to]	16,50	0
Reststoffdeponie [to]	31,50	100.800
Massenabfalldeponie [to]	34,50	110.400
Disposal ALSAG:		
Baurestmassen [to]	8,00	0
Reststoffdeponie [to]	18,00	57.600
Massenabfalldeponie [to]	26,00	83.200
Costs for disposal [€]		**352.000**
Costs for excavation and disposal [€]		658.350
Costs for planning, site supervision, construction site burden costs 10% of overall c		**65.835**
Overall costs [€]		**724.186**

The following pages provide an explanation of the program's operating mode. The input and output parameters are written cursive in order to assure a better readability of the following pages.

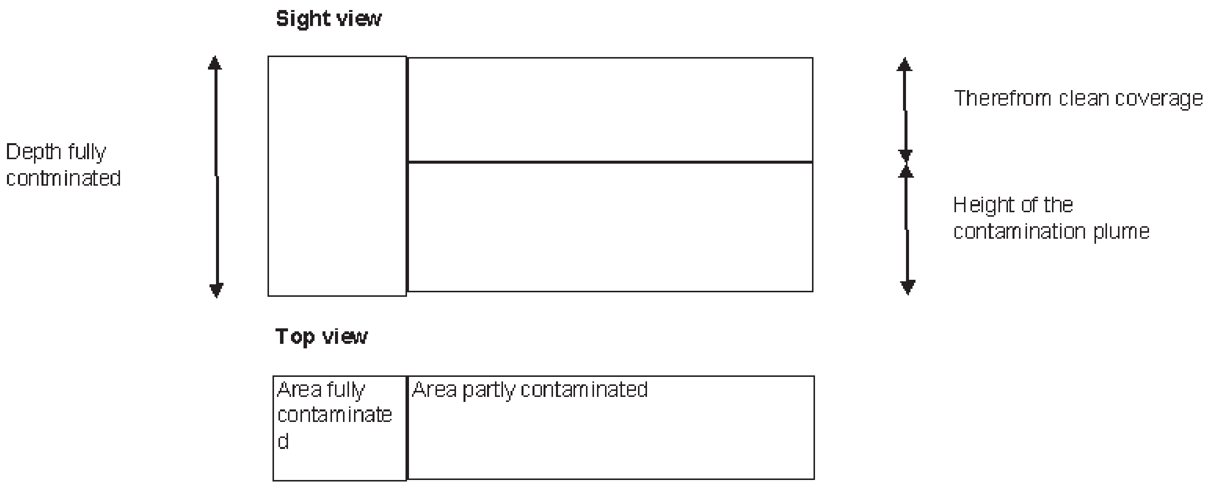
Input parameters

The green, yellow and grey cells represent the input parameters that have to be inserted in order to calculate the excavation costs for the different projects.

Green cells

The green cells represent the different extent of the contaminations for the nine investigated insitu projects. They need to be changed for every project. The extent of the contamination is summed up, in a table, at the beginning of the project description. The following illustration explains the meaning of the spatial extent of the contamination.

Graphical illustration of spatial extent of contamination



Yellow cells

The yellow cells also represent input parameters; they have been provided by OMV and have the same values for all of the nine investigated projects.

Distance to disposal facility: The contaminated material has to be brought to the disposal facility. The duration for the outgoing and the return transport (with a lorry) is assumed to be 4.5 hours. The input parameter, *distance to disposal facility*, is connected with the *lorry costs that accumulate for contaminated material.*

Difficulty factor: The overall excavation costs are multiplied with the difficulty factor. The factor was provided by OMV and is set with a value of 1.3 for the following simulations. The reason why a difficulty factor is applied is that there is installed equipment which has to be removed during the excavation process.

Expected degree of contamination:

The material which is brought to the disposal facility can be contaminated either to the threshold value for Baurestmassen, Reststoffdeponie or Massenabfalldeponie. For the following simulations it was assumed that 50% of the volume was contaminated to the threshold value for Massenabfalldeponie and 50% to the threshold value for Reststoffdeponie. These values were provided by OMV.

Grey cells

Input cost parameters (used with @ risk)

The following cost parameters have been provided by OMV. The minimum, most likely and maximum costs are summed up in the next table. Those costs are depicted either in €/m³, €/to, or €/h.

Table 21: Cost data for excavation and disposal

	Minimum Costs	Most Likely Costs	Maximum Costs
Removal of the top-soil [€/m³]	2,00	2,30	2,60
Work with digger until 5m, removal and assembly of material:			
Dry material [€/m³]	2,3	2,7	3,1
Wet material [€/m³]	2,9	4,8	5,9
Work with digger from 5 – 10 m, removal and assembly of material:			
Dry material [€/m³]	2,76	3,24	3,72
Wet material [€/m³]	3,48	5,76	7,08
Work with digger from 10 – 15 m, removal and assembly of material:			
Dry material [€/m³]	3,31	3,89	4,47
Wet material [€/m³]	4,18	6,91	8,50
Work with digger from 15 – 20 m, removal and assembly of material:			

Dry material [€/m³]	3,97	4,67	5,37
Wet material [€/m³]	4,76	8,29	10,20
Costs of exchange material [€/m³]	7,00	10,00	13,00
Lorry costs [€/h]	55,00	60,00	65,00
Wheel loader costs [€/h]	55,00	60,00	65,00
Disposal of contaminated material until the threshold value for:			
Baurestmassen [€/to]	14,00	16,50	19,00
Reststoffdeponie [€/to]	28,00	31,50	35,00
Massenabfalldeponie [€/to]	27,00	34,50	42,00
Disposal ALSAG:			
Baurestmassen [€/to]	8,00	8,00	8,00
Reststoffdeponie [€/to]	18,00	18,00	18,00
Massenabfalldeponie [€/to]	26,00	26,00	26,00

Monte Carlo Simulation

When excavation has to be performed at a contaminated site there are certain risks, concerning the costs of the project, which have to be considered. When the costs of the single steps (such as the costs from the table above) are uncertain, a method is needed where all the risks of the single steps are assessed simultaneously and the effects of those risks on the overall costs are considered. The Monte Carlo method has been used for that purpose within this thesis.

Monte Carlo Simulation is a method for modelling the value of uncertain variables in forecasting. It uses probability distributions for uncertain independent input variables and runs several tests (in the simulations 10.000 iterations were used) along these distributions in order to estimate a range of values for the output (dependent) variables. The outcome of the simulation is normal distributed.[129]

The program @risk was used for the calculation of excavation costs (which is based on the concept of Monte Carlo Simulation). The minimum, most likely and maximum excavation costs have been calculated. The probability that the excavation costs lie between the minimum and maximum costs is 90% for all of the investigated projects.

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[129] HULETT D. (2004), p.1 ff.

The values in the table above represent the input parameters of the Monte Carlo Simulation.

For the input parameters triangular distributions were used. The triangular distribution is recommended in the literature for cases where the cost data is based on the judgement of experts which define a minimum, most likely and a maximum cost value such as it is the case with the cost input parameters in the figure above.[130]

The following screenshot illustrates:

- the input parameters of the Monte Carlo Simulation
- the connection of the input parameters with the associated parameters
- and the output parameter of the Monte Carlo Simulation: for every output parameter you obtain the minimum, most likely and maximum costs (whereby the probability that the costs fall in the range of the minimum and the maximum costs is 90%)

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[130] BUSCH T. (2005), p.164

Monte Carlo Input variables	Connected with (multiplied with):	Monte Carlo Output variables
Removal of the top-soil [€/m³]	Volume of the topsoil [m³]	Costs for removal of the topsoil [€]
Work with digger until 5m, Dry Material [€/m³]	Volume of dry material until 5 m [m³]	Costs for work with digger until 5m,dry material [€]
Work with digger until 5m, Wet Material [€/m³]	Volume of wet material until 5m [m³]	Costs for work with digger until 5m, wet material [€]
Work with digger 5 - 10m, Dry Material [€/m³]	Volume of dry material from 5 - 10m [m³]	Costs for work with digger 5 - 10m, dry material [€]
Work with digger 5 - 10m, Wet Material [€/m³]	Volume of wet material from 5 - 10m [m³]	Costs for work with digger 5 - 10m, wet material [€]
Work with digger 10 - 15m, Dry Material [€/m³]	Volume of dry material from 10 - 15m [m³]	Costs for work with digger 10 - 15m, dry material [€]
Work with digger 10 - 15m, Wet Material [€/m³]	Volume of wet material from 10 - 15m [m³]	Costs for work with digger 10 - 15m, wet material [€]
Work with digger 15 - 20m, Dry Material [€/m³]	Volume of dry material from 15 -20m [m³]	Costs for work with digger 15 -20m, dry material [€]
Work with digger 15 - 20m, Wet Material [€/m³]	Volume of wet material from 15 -20m [m³]	Costs for work with digger 15 - 20m, wet material [€]
Exchange material [€/m³]	Volume of exchange material [m³]	Costs for exchange material [€]
Evacuation and return transport of partly sideways bedded material [€/h]	Duration of transport for partly sideways bedded material [h]	Costs for partly sideways stored material [€]
Evacuation on a storing place and loading on a lorry of wet contaminated material [€/h]	Duration of transport and loading for wet contaminated material [h]	Costs for evacuation and loading of wet material [€]
Lorry for contaminated material [€/h]	Duration of transport for contaminated material [h]	Lorry costs for contaminated material [€]
Disposal to threhold value for Baurestmassen [€/to]	Weight of material contaminated to threshold value for Baurestmassen [to]	Disposal costs for threshold value to Baurestmassen [€]
Disposal to threhold value for Reststoffdeponie [€/to]	Weight of material contaminated to threshold value for Reststoffdeponie [to]	Disposal costs for threshold value to Reststoffdeponie [€]
Disposal to threhold value for Massenabfalldeponie [€/to]	Weight of material contaminated to threshold value for Massenabfalldeponie [to]	Dispoal costs for threshod value to Massenabfalldeponie [€]
ALSAG Disposal for Baurestmasssen [€/to]	Weight of material contaminated to threshold value for Baurestmassen [to]	ALSAG costs for threshold value to Baurestmassen [€]
ALSAG Dispoal for Reststoffdeponie [€/to]	Weight of material contaminated to threshold value for Reststoffdeponie [to]	ALSAG costs for threshold value to Reststoffdeponie [€]
ALSAG Dispoal for Massenabfalldeponie [€/to]	Weight of material contaminated to threshold value for Massenabfalldeponie [to]	ALSAG costs for threshold value to Massenabfalldeponie [€]

If you add up the orange cells you obtain the minimum, most likely and maximum costs which accumulate for excavation. If you add up the turquoise cells you obtain the minimum, most likely and maximum costs which accumulate for the disposal of contaminated material. These costs represent the results of the @risk simulation. They are presented in a table within the project descriptions.

Red cells

Costs for excavation consist of:

Overall digger costs: The entire volume has to be excavated and refilled. The entire volume consists of the *area fully contaminated (m²)*, which has to be multiplied by the *depth fully contaminated (m)* plus the *area partly contaminated (m²)*, multiplied by the sum of *there from clean coverage (m)* and the *height of the contamination plume (m)*.

The entire volume (m³) multiplied by the *digger costs (€/m³)* and multiplied by 2 (for removal and reassembly) result in the *overall digger costs (€)*. The digger costs that accumulate depend on the material; there are different prices for dry and wet material and for the depth to which the material is contaminated. The costs for excavation increase with increasing depth because of acclivity work that has to be carried out; so the costs for excavation are multiplied by a factor of 1.2 for every 5 meters of depth being excavated. Once the groundwater table is reached, the excavation costs also increase because of additional work that has to be done for the treatment of contaminated groundwater. That is the reason for the different prices which accumulate for the excavation of dry and wet material.

Costs for exchange material: The contaminated material has to be replaced by exchange material. The volume of contaminated material is equal to the volume of exchange material. The *volume of contaminated material (m³)* has to be multiplied by the *costs for exchange material (€/m³)* in order to obtain the *costs that accumulate for the exchange material (€)*. The transport of the material to the contaminated site is also included in the costs for exchange material.

Evacuation and return transport of partly sideways bedded material: The *partly contaminated area (m²)* multiplied by *there from clean coverage (m)* represents the volume of material that is partly sideways stored. The material (which is not contaminated) is brought sideways with the help of a wheel loader. The wheel loader is able to transport 3 m³ of material per ride. The *volume of partly sideways stored material (m³)* divided by the *capacity of the wheel loader (3 m³)* represents the *number of roundtrips* that have to be carried out in order to transport the entire volume to the storage place. One roundtrip for the wheel loader is calculated with 10 minutes (for the loading of the material, the trip to the storage place and the return trip). So the *number of roundtrips* multiplied by the *duration of the roundtrip* (10 minutes), multiplied by the *costs for the wheel loader (€/h)*, multiplied by 2 (for removal and assembly) represent the costs that accumulate for the *evacuation and return transport of partly sideways stored material (€)*.

Evacuation on a storing place and loading on a lorry of wet contaminated material: The wet contaminated material is stored at a storing place in order to let the wet material drip off; this reduces the weight of the contaminated material. The wet contaminated material is transported with the help of a wheel loader. Once the wet contaminated material has dripped off, it is loaded on a lorry and transported to the disposal facility. The wheel loader is able to transport 3 m³ of material per ride. The volume of wet contaminated material (m³), divided by the capacity of the wheel loader (3 m³), represents the number of roundtrips that have to be done in order to transport the wet contaminated volume to the storage place.

One roundtrip with the wheel loader and loading the lorry is calculated with 16 minutes. The 16 minutes consist of loading the material, the trip to the storage place, loading the lorry and the return trip. So the *number of roundtrips* multiplied by the *duration of the roundtrips (16 minutes)*, multiplied by the *costs for the wheel loader (€/h)*, represents the costs that accumulate for *evacuation on a storing place and loading of wet contaminated material (€).*

Lorry costs for contaminated material: The contaminated material is brought to the disposal facility. One lorry is capable of transporting 18 m³ of material. The *contaminated volume (m³)* divided by the *transporting capacity (m³)* represents the *number of trips* that have to be undertaken in order to transport the entire contaminated material to the disposal facility. The *number of trips* multiplied by the *duration of the roundtrip* (4.5 hours), multiplied by the *costs for the lorry (€/h)*, represents the *lorry costs that accumulate for the contaminated material (€).*

Costs for disposal and associated ALSAG charges:

Disposal of material which is contaminated to the threshold for Baurestmassen: The fraction of volume which is contaminated to the threshold value for Baurestmassen has to be entered at the input parameter *contaminated to the threshold value for Baurestmassen*. This fraction is 0 for all of the investigated projects.

Note: The disposal of contaminated material for Baurestmassen has been included in this simulation, for the calculation of the excavation costs of future projects, where the Baurestmassen could make up a considerable part of the fraction of contaminated material.

Disposal of material which is contaminated to the threshold for Reststoffdeponie: The fraction of volume which is contaminated to the threshold value for Reststoffdeponie has to be entered at the input parameter *contaminated to the threshold value for Reststoffdeponie*. This fraction is 0.5 for all of the investigated projects. 0.5 has to be multiplied by the contaminated volume (to) and by the costs for disposal of Reststoffdeponie (€/to). This results in the disposal costs of material which is contaminated to the threshold value for Reststoffdeponie (€).

Disposal of material which is contaminated to the threshold for Massenabfalldeponie: The fraction of volume which is contaminated to the threshold value for Massenabfalldeponie has to be entered at the input parameter *contaminated to the threshold value for Massenabfalldeponie*. This fraction is 0.5 for all of the investigated projects. 0.5 has to be multiplied by the contaminated volume (to) and by the costs for disposal of Massenabfalldeponie (€/to). This results in the disposal costs of material which is contaminated to the threshold value for Massenabfalldeponie (€).

ALSAG charges for Baurestmassen:

The fraction of volume which is contaminated to the threshold value for Baurestmassen has to be entered at the input parameter *contaminated to the threshold value for Baurestmassen*. This fraction is 0 for all of the investigated projects.

Note: The ALSAG charges which have to be paid for the disposal of material that is contaminated to Baurestmassen has been included in this simulation, for the calculation of the excavation costs of future projects, where the Baurestmassen could make up a considerable part of the fraction of contaminated material.

ALSAG charges for Reststoffdeponie:

The fraction of volume which is contaminated to the threshold value for Reststoffdeponie has to be entered at the input parameter *contaminated to the threshold value for Reststoffdeponie*. This fraction is 0.5 for all of the investigated projects. 0.5 has to be multiplied by the contaminated volume (to) and by the ALSAG charges for Reststoffdeponie (€/to). This results in the costs that accumulate for the ALSAG charges (€) for material that is contaminated to the threshold value for Reststoffdeponie.

ALSAG charges for Massenabfalldeponie:

The fraction of volume which is contaminated to the threshold value for Massenabfalldeponie has to be entered at the input parameter *contaminated to the threshold value for Massenabfalldeponie*. This fraction is 0.5 for all of the investigated projects. 0.5 has to be multiplied by the contaminated volume (to) and by the ALSAG charges (€/to). This results in the costs that accumulate for the ALSAG charges (€) for material that is contaminated to the threshold value for Massenabfalldeponie.

Note: All the data which was above used such as the duration of roundtrips, transport capacity of wheel loader and lorry or the fractions of contaminated material has been provided by OMV.

Costs for planning, site supervision and construction site burden costs

The costs for planning, site supervision and construction site burden costs are calculated with 10% (due to experience) of the sum of the excavation plus the disposal costs. This value has been provided by OMV.

Blue cells

The three main output categories of the simulation consist of:

- Costs for excavation
- Costs for disposal and associated ALSAG charges
- Costs for planning, site supervision and construction site burden costs

➔ The sums of these three main output categories result in the overall excavation costs.

The three main output categories and the overall excavation costs are summed up in the tables of the project description for the nine investigated projects.

Conversion factors

All the material which is located under the groundwater table is assumed to be wet material and everything above the groundwater table is assumed to be dry material. The following equation was used in order to separate the dry from the wet material:

Groundwater table [m] = Depth fully contaminated [m] – There from clean coverage [m]

The soil has a different mass depending on its initial condition; the following conversion factors are used within the simulation:

- Embedded soil: 1 m^3 equates to 2 tons
- Dry loose soil: 1 m^3 equates to 1.6 tons
- Wet loose soil: 1 m^3 equates to 1.8 tons

The conversion factors have been provided by OMV.

7.3 Allocation of insitu costs

As it was noted before, the installation and operating costs are divided into different fractions. This disposition is important in order to be able to investigate the main cost causers of insitu projects. The allocation of the insitu costs is provided in the following because those costs are presented in a table, for all of the investigated projects, within the project description that is provided in the next chapter of the thesis.

Allocation of installation costs for insitu projects

The installation costs are divided into costs that accumulate for:

- Project management (Project Mgmt.)
- Digging of decontamination trenches, drilling of groundwater wells (Digging of trenches)
- Mounting and installation of the decontamination facility (Mounting of facility)
- Installing of the pipe system and associated excavation (Pipes and associated excavation)
- Installation of the monitoring system (Monitoring system)
- Regulation of the decontamination facility, measurement and control technology, software (Regulation of facility)
- Start-up of the decontamination facility (Start up of facility)
- Removal of contaminated material
- Crop damage
- Diverse other costs

The abbreviations within the brackets are used in the figures of the project description which show the costs of the different fractions for the investigated projects.

Allocation of operating costs for insitu projects

The operating costs are divided into the following three main categories:

1) Supervision of the operations
2) Maintenance and repair of mechanical parts of the decontamination facility
3) Measurement and control technology and software support.

The supervision of the operations can be further subdivided into the following costs:

- Fieldwork: External work which is necessary if ongoing operations are interrupted or on-site inspections have to be carried out.

- Laboratory analysis (Lab analysis): Consist of the control of the water quality within the decontamination facility, executions of groundwater measurements and the associated analysis of the measurements.
- Current controls: The regulation of the decontamination facility, coordination and control of maintenance work and supervising of maintenance offers and invoices which have to be carried out.
- Operations concerning the collaboration with the authorities (Work with authority): An annual report has to be submitted to the authorities which concerns the documentation of the ongoing decontamination operations.
- Diverse other costs: concerning the supervision of the operations

Maintenance and repair of the mechanical parts of the decontamination facility can be further subdivided into the following costs:

- Travel time to the contaminated site
- Working time for maintenance and repair for the mechanical parts of the facility (Working time for m&r)
- Costs of the material for maintenance and repair of mechanical parts of the facility (Material costs for m&r)
- Diverse other costs: concerning the maintenance and repair of the mechanical parts of the decontamination facility

Measurement and control technology and software support can be subdivided into the following costs:

- Lump sum maintenance for measurement and control technology and software transport (Lump sum for steering)
- Costs of the material for measurement and control technology software
- Inspection of electrical parts of the facility (TÜV)
- Diverse other costs concerning measurement and control technology and software transport

7.4 Project descriptions for small contaminated volume (0 m³ - 10.000 m³)

The cost data (for small projects) is available for one pump and treat project, one pneumatic project and one monitoring project.

7.4.1 Pump and treat Project D – Con. Vol. 3.200 m³

Data for the extent of the contamination concerning the pump and treat project D is given in the following table:

Contaminated volume [m³]	3.200
Area fully contaminated [m²]	0
Area partly contaminated [m²]	1.600
Depth fully contaminated [m]	6.5
Height of the contamination plume [m]	2
There from clean coverage [m]	4.5

The next two tables gives a detailed overview of the distribution of the installation and the operating costs for project D:

Project D	Installation Costs
Regulation of facility	20.800 €
Digging of trenches	12.500 €
Mounting of facility	12.500 €
Monitoring system	12.000 €
Project Mgmt.	9.300 €
Crop damage	4.000 €
Pipes and associated excavation	3.500 €
Divers other costs	2.000 €

Project D	Operating Costs
Lump sum for steering	10.000 €
Working time for m&r	8.000 €
Lab analysis	4.000 €
Current controls	3.000 €
Material costs for m&r	2.000 €
Divers other costs	1.000 €

The overall installation costs and the discounted costs of the three subcategories of the operating costs over the scheduled duration, and the resulting overall costs, are shown in the next table:

Year of erection of decontamination facility	2005
Scheduled duration of decontamination measuers [ys]	5
Installation costs [€]	76.600
Costs for supervision of the operations [€]	30.306
Costs for maintenance and repair [€]	43.295
Costs for measurement and control technology [€]	47.624
Overall costs [€]	197.825

The costs per contaminated volume are approx. 62 €/m³ for project D.

Predicted excavation and disposal costs for project D

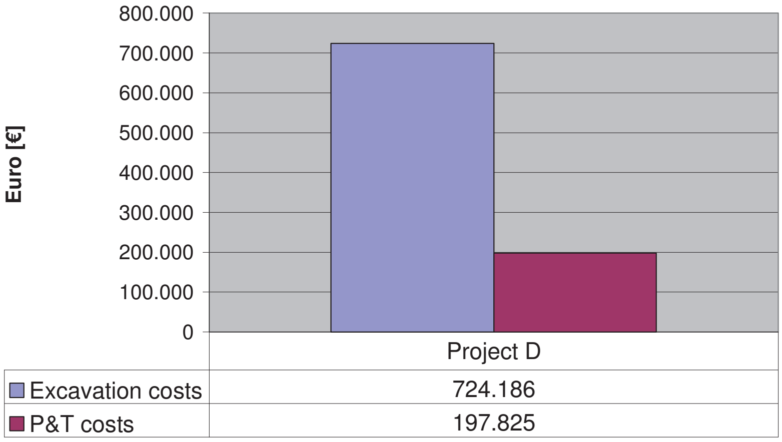
The probability that the costs lie between the minimum costs and maximum costs is 90%.

	Minimum costs	Most likely costs	Maximum costs
Costs of excavation [€]	271.557	306.350	337.003
Costs of disposal [€]	334.000	352.000	370.400
Costs for planning, site supervision, construction site burden costs 10% [€]	60.556	65.835	70.740
Overall costs [€]	666.113	724.185	778.143

The costs per contaminated volume for the most likely case are approx. 226 €/m³.

Economic comparison of pump and treat and excavation for project D

I will always compare the costs of the insitu method and the most likely costs of the excavation option for the following economic comparisons.



If excavation would have been performed instead of pump and treat for project D the costs would have been approx. 3.7 times higher.

7.4.2 Soil vapour extraction Project J – Con. Vol. 2.100 m³

Data for the extent of the contamination concerning the soil vapour extraction project J is given in the following table:

Contaminated volume [m³]	2.100
Area fully contaminated [m²]	0
Area partly contaminated [m²]	750
Depth fully contaminated [m]	4.8
Height of the contamination plume [m]	2.8
There from clean coverage [m]	2

The next two tables give a detailed overview of the distribution of the installation and the operating costs for project J:

Project J	**Installation Costs**
Pipes and associated excavation	14.652 €
Mounting of facility	12.413 €
Digging of trenches	10.456 €
Project Mgmt.	3.381 €
Disposal of contaminiated material	1.163 €
Divers other costs	1.010 €

Project J	**Operating Costs**
Current controls	32.220 €
Field work	10.347 €
Lump sum for steering	7.203 €
Divers other costs	5.254 €
Work with authority	3.994 €

The installation costs and the discounted costs of the three subcategories of the operating costs over the scheduled duration, and the resulting overall costs, are shown in the next table:

Year of erection of decontamination facility	2005
Scheduled duration of decontamination measuers [ys]	3
Installation costs [€]	43.075
Costs for supervision of the operations [€]	39.054
Costs for maintenance and repair [€]	14.308
Costs for measurement and control technology [€]	19.616
Overall costs [€]	203.796

The costs per contaminated volume are approx. 97 €/m³.

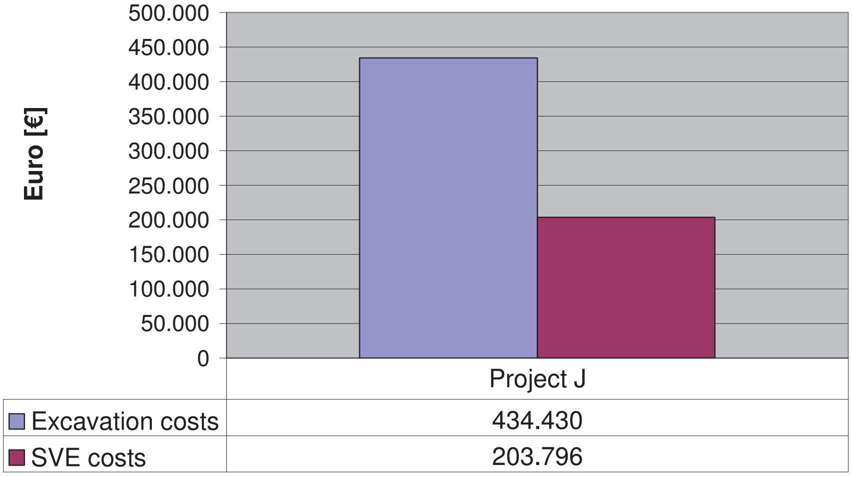
Predicted excavation and disposal costs for project J

The probability that the costs lie between the minimum costs and maximum costs is 90%.

	Minimum costs	Most likely costs	Maximum costs
Costs of excavation [€]	142.920	163.936	183.452
Costs for disposal [€]	219.220	231.000	242.490
Costs for planning, site supervision, construction site burden costs 10% [€]	34.210	39.494	42.594
Overall costs [€]	396.350	434.430	468.536

The costs per contaminated volume are approx. 207 €/m³ for Project J.

Economic comparison of soil vapour extraction and excavation for Project J



The excavation costs are approx. 2.1 times higher than for soil vapour extraction.

7.4.3 Monitoring Project I – Con. Vol. 6.000 m³

Data for the extent of the contamination for the monitoring project I is given in the next table:

Contaminated volume [m³]	6.000
Area fully contaminated [m²]	1.000
Area partly contaminated [m²]	2.000
Depth fully contaminated [m]	4
Height of the contamination plume [m]	1
There from clean coverage [m]	14

The next two tables gives a detailed overview of the distribution of the installation and the operating costs for project I:

Project I	Installation Costs
Monitoring system	12.000 €
Project Mgmt.	4.000 €
Crop damage	2.000 €
Divers other costs	2.000 €

Project I	Operating Costs
Work with authority	4.000 €
Divers other costs	4.000 €
Lab analysis	1.000 €
Working time for m&r	1.000 €

The installation costs and the discounted costs of the three subcategories of the operating costs over the scheduled duration, and the resulting overall costs, are shown in the next table:

Year of erection of decontamination facility	2005
Scheduled duration of decontamination measuers [ys]	10
Installation costs [€]	20.000
Costs for supervision of the operations [€]	38.609
Costs for maintenance and repair [€]	7.722
Costs for measurement and control technology [€]	30.887
Overall costs [€]	97.217

The costs per contaminated volume for project I are approx. 16 €/m³.

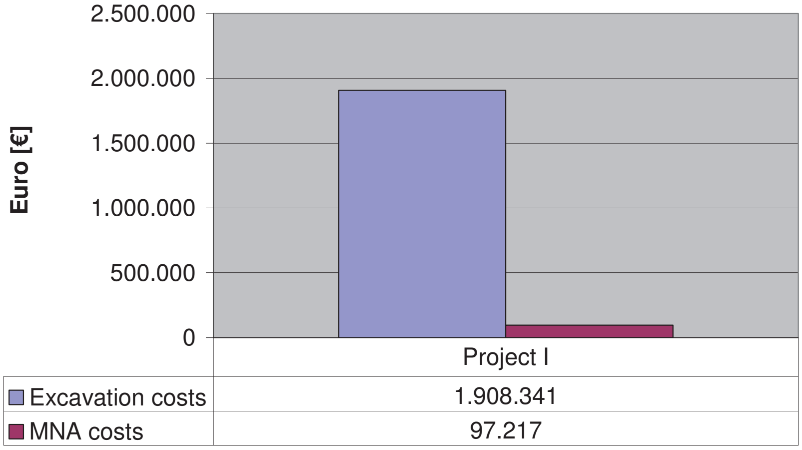
Predicted excavation costs for project I

The probability that the costs lie between the minimum costs and maximum costs is 90%.

	Minimum costs	Most likely costs	Maximum costs
Costs of excavation [€]	977.943	1.074.855	1.157.778
Costs for disposal [€]	626.600	660.000	692.900
Costs for planning, site supervision, construction site burden costs 10% [€]	160.454	173.486	185.068
Overall costs [€]	1.764.997	1.908.341	2.035.746

The costs per contaminated volume for the most likely case are approx. 318 €/m³.

Economic comparison of Monitoring and excavation for project I



The costs for excavation and disposal are approx.19.6 times higher than the monitoring costs for Project I.

7.5 Project descriptions for average contaminated volume (10.000 m³ - 50.000 m³)

For average contaminated volume the data for three pump and treat projects and one monitoring project is available.

7.5.1 Pump and treat Project E – Con. Vol. 27.000 m³

Data for the extent of the contamination for the pump and treat project E is given in the next table:

Contaminated volume [m³]	27.000
Area fully contaminated [m²]	0
Area partly contaminated [m²]	18.000
Depth fully contaminated [m]	4.5
Height of the contamination plume [m]	1.5
There from clean coverage [m]	3

The next two tables give a detailed overview of the distribution of the installation and the operating costs for project E:

Project E	Installation Costs
Regulation of facility	45.502 €
Pipes and associated excavation	33.356 €
Project Mgmt.	21.985 €
Monitoring system	10.000 €
Mounting of facility	7.100 €
Digging of trenches	6.740 €
Start up of facility	5.000 €

Project E	Operating Costs
Current controls	6.500 €
Lab analysis	5.000 €
Working time for m&r	2.000 €
Material costs for m&r	1.500 €
Work with authority	1.000 €
Divers other costs	1.000 €

The installation costs and the discounted costs of the three subcategories of the operating costs over the scheduled duration, and the resulting overall costs, are shown in the next table:

Year of erection of decontamination facility	2004
Scheduled duration of decontamination measuers [ys]	10
Installation costs [€]	129.683
Costs for supervision of the operations	96.522
Costs for maintenance and repair [€]	27.026
Costs for measurement and control technology [€]	7.722
Overall costs [€]	260.952

The costs per contaminated volume for Project E are approx. 10 €/m³.

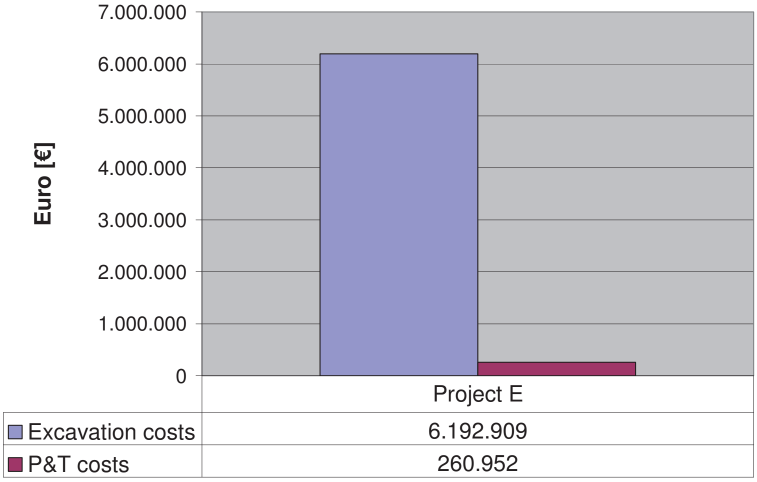
Predicted excavation costs for project E

The probability that the costs lie between the minimum costs and maximum costs is 90%.

	Minimum costs	Most like costs	Maximum costs
Costs of excavation [€]	2.307.351	2.659.917	2.943.225
Costs for disposal [€]	2.817.400	2.970.000	3.122.800
Costs for planning, site supervision, construction site burden costs 10% [€]	512.475	562.992	606.603
Overall costs [€]	5.637.226	6.192.909	6.672.628

The costs per contaminated volume for the most likely case are approx. 229 €/m³.

Economic comparison of pump and treat and excavation for project E



	Project E
▨ Excavation costs	6.192.909
■ P&T costs	260.952

The costs for excavation and disposal are approx. 23.7 times higher than the pump and treat costs for Project E.

7.5.2 Pump and treat Project F – Con. Vol. 30.000 m³

Data for the extent of the contamination for the pump and treat project F is given in the next table:

Contaminated volume [m³]	30.000
Area fully contaminated [m²]	0
Area partly contaminated [m²]	30.000
Depth fully contaminated [m]	4.5
Height of the contamination plume [m]	1
There from clean coverage [m]	3.5

The next two tables give a detailed overview of the distribution of the installation and the operating costs for project F:

Project F	Installation Costs
Regulation of facility	76.737 €
Pipes and associated excavation	42.105 €
Project Mgmt.	31.454 €
Mounting of facility	31.100 €
Digging of trenches	25.147 €
Monitoring system	8.000 €
Other installation costs	10.000 €

Project F	Operating Costs
Current controls	10.000 €
Lab analysis	9.900 €
Working time for m&r	8.000 €
Divers other costs	7.000 €
Material costs for m&r	4.000 €
Work with authority	2.000 €
Lump sum for steering	2.000 €

The installation costs and the discounted costs of the three subcategories of the operating costs over the scheduled duration, and the resulting overall costs, are shown in the next table:

Year of erection of decontamination facility	2004
Scheduled duration of decontamination measuers [ys]	10
Installation costs [€]	224.543
Costs for supervision of the operations	169.106
Costs for maintenance and repair [€]	92.661
Costs for measurement and control technology [€]	69.496
Overall costs [€]	555.805

The costs per contaminated volume are approx. 19 €/m³.

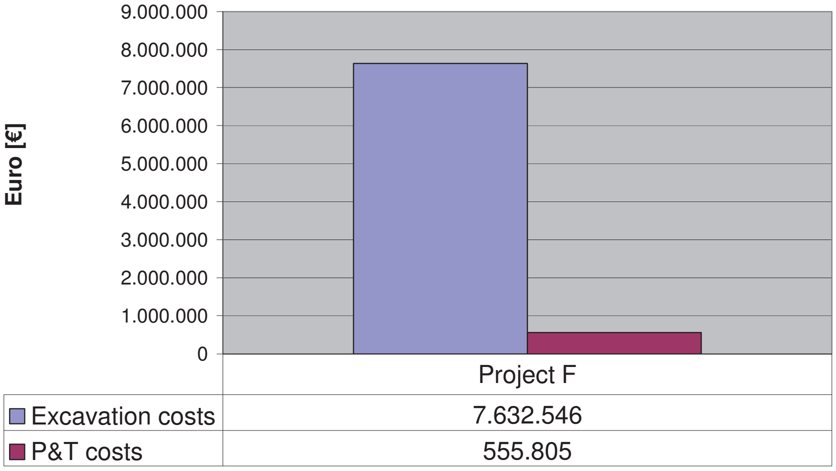
Predicted excavation costs for project F

The probability that the costs lie between the minimum cost and maximum costs is 90%.

	Minimum costs	Most likely costs	Maximum costs
Costs of excavation [€]	3.232.493	3.638.678	4.071.810
Costs for disposal [€]	3.135.000	3.300.000	3.470.000
Costs for planning, site supervision, construction site burden costs 10% [€]	636.749	693.868	754.181
Overall costs [€]	7.004.242	7.632.546	8.295.991

The costs per contaminated volume for the most likely case are approx. 254 €/m³.

Economic comparison of pump and treat and excavation for Project F



	Project F
🟦 Excavation costs	7.632.546
🟥 P&T costs	555.805

The costs for excavation and disposal are approx. 13.7 times higher than the pump and treat costs for project F.

7.5.3 Pump and treat Project G – Con. Vol. 40.000 m³

Data for the extent of the contamination for the pump and treat project G is given in the next table:

Contaminated volume [m³]	40.000
Area fully contaminated [m²]	5.000
Area partly contaminated [m²]	15.000
Depth fully contaminated [m]	5
Height of the contamination plume [m]	1
There from clean coverage [m]	2

The next two tables give a detailed overview of the distribution of the installation and the operating costs for project G:

Project G	Installation Costs
Mounting of facility	20.000 €
Digging of trenches	16.570 €
Disposal of material	16.000 €
Start up of facility	16.000 €
Project Mgmt.	12.300 €
Regulation of facility	11.370 €
Pipes and associated excavation	7.323 €
Other installation costs	11.186 €

Project G	Operating Costs
Work with authority	7.000 €
Laboratory analysis	5.000 €
Current controls	4.000 €
Working time for m&r	2.000 €
Material costs for m&r	2.000 €
Divers other costs	2.000 €

The installation costs and the discounted costs of the three subcategories of the operating costs over the scheduled duration, and the resulting overall costs, are shown in the next table:

Year of erection of decontamination facility	2007
Scheduled duration of decontamination measuers [ys]	7
Installation costs [€]	110.749
Costs for supervision of the operations	98.368
Costs for maintenance and repair [€]	23.145
Costs for measurement and control technology [€]	5.786
Overall costs [€]	238.049

The costs per contaminated volume are approx. 6 €/m³.

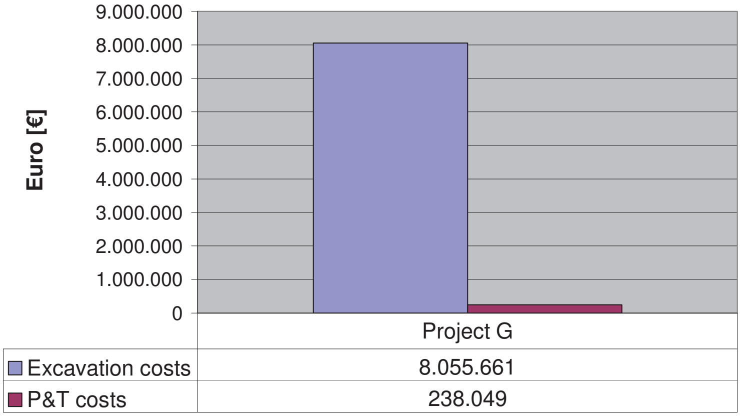
Predicted excavation costs for project G

The probability that the costs lie between the minimum costs and maximum costs is 90%.

	Minimum costs	Most likely costs	Maximum costs
Costs of excavation [€]	2.504.742	2.923.328	3.260.723
Costs for disposal [€]	4.180.000	4.400.000	4.629.000
Costs for planning, site supervision, construction site burden costs 10% [€]	668.474	732.333	788.972
Overall costs [€]	7.353.216	8.055.661	8.678.695

The costs per contaminated volume for the most likely case are approx. 201 €/m³.

Economic comparison of pump and treat and excavation for Project G



The costs for excavation and disposal are approx. 33.8 times higher than the pump and treat costs for Project G.

7.5.4 Monitoring Project H – Con. Vol. 25.000 m³

Data for the extent of the contamination for the monitoring project H is given in the next table:

Contaminated volume [m³]	25.000
Area fully contaminated [m²]	1.000
Area partly contaminated [m²]	2.000
Depth fully contaminated [m]	17
Height of the contamination plume [m]	4
There from clean coverage [m]	12

The next two tables give a detailed overview of the distribution of the installation and the operating costs for project H:

Project H	Installation Costs
Monitoring system	20.000 €
Digging of trenches	6.000 €
Divers other costs	3.000 €
Crop damage	1.000 €

Project H	Operating Costs
Work with authority	4.000 €
Field work	2.000 €
Lab analysis	2.000 €
Current controls	2.000 €

The installation costs and the discounted costs of the three subcategories of the operating costs over the scheduled duration, and the resulting overall costs, are shown in the next table:

Year of erection of decontamination facility	2007
Scheduled duration of decontamination measuers [ys]	10
Installation costs [€]	30.000
Costs for supervision of the operations [€]	77.217
Costs for maintenance and repair [€]	0
Costs for measurement and control technology [€]	0
Overall costs [€]	107.217

The costs per contaminated volume for project H are approx. 4 €/m³.

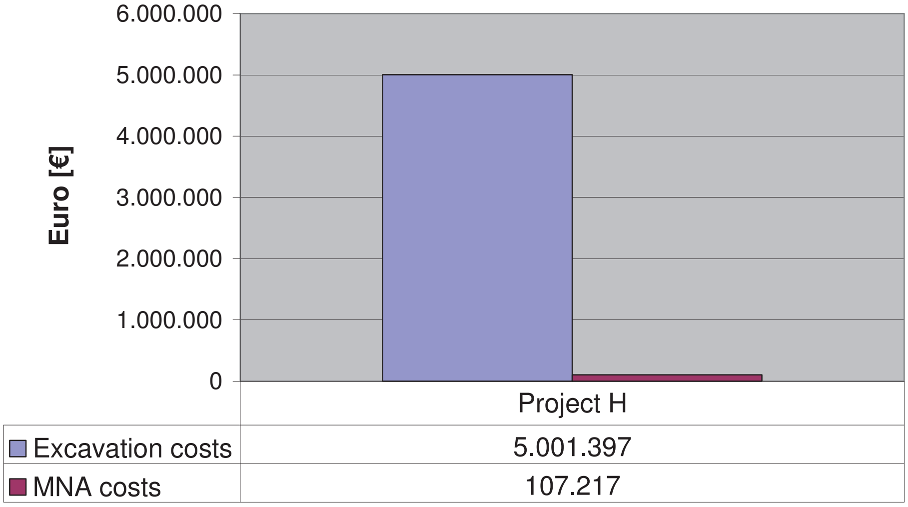
Predicted excavation costs for project H

The probability that the costs lie between the minimum costs and maximum costs is 90%.

	Minimum costs	Most likely costs	Maximum costs
Costs of excavation [€]	1.577.951	1.796.725	1.988.053
Costs for disposal [€]	2.604.300	2.750.000	2.891.200
Costs for planning, site supervision, construction site burden costs 10% [€]	418.225	454.672	487.925
Overall costs [€]	4.600.476	5.001.397	5.367.178

The costs per contaminated volume for the most likely case are approx. 200 €/m³.

Economic comparison of pump and treat and excavation for Project H



	Project H
■ Excavation costs	5.001.397
■ MNA costs	107.217

The costs for excavation and disposal are approx. 46.6 times higher than the monitoring costs for Project H.

7.6 Project description for large contaminated volume (50.000 m^3 - 500.000 m^3)

Data (for large contaminated volume) is available for two pump and treat projects.

7.6.1 Pump and treat Project A+B – Con. Vol. 167.850 m^3

Although the installation costs of Project A and Project B are listed separately the operating costs are summed up together for both projects, so in the following I will examine Project A and Project B as one Project.

Data for the extent of the contamination for the pump and treat project A is given in the next table:

Contaminated volume [m^3]	110.450
Area fully contaminated [m^2]	21.500
Area partly contaminated [m^2]	27.500
Depth fully contaminated [m]	3.5
Height of the contamination plume [m]	1.28
There from clean coverage [m]	2.22

Data for the extent of the contamination for the pump and treat project B is given in the next table:

Contaminated volume [m^3]	57.400
Area fully contaminated [m^2]	0
Area partly contaminated [m^2]	29.800
Depth fully contaminated [m]	3.91
Height of the contamination plume [m]	1.93
There from clean coverage [m]	1.98

The next table gives a detailed overview of the distribution of the installation costs for project A:

Project A	Installation Costs
Regulation of facility	354.512
Mounting of facility	351.747
Pipes and associated excavation	200.000
Digging of trenches	199.402
Project Mgmt.	146.543
Start up of facility	75.672
Monitoring system	58.333
Other installation costs	39.552

The next table gives a detailed overview of the distribution of the installation costs for project B:

Project B	Installation Costs
Mounting of facility	262.363 €
Digging of trenches	242.840 €
Pipes and associated excavation	200.000 €
Regulation of facility	167.865 €
Disposal of material	159.600 €
Project Mgmt.	159.000 €
Crop damage	35.000 €
Other installation costs	57.127 €

The next table gives a detailed overview of the distribution of the operating costs of project A+B that accumulated for one year:

Project A+B	Operating Costs
Current controls	55.448 €
Lab analysis	30.124 €
Work with authority	21.600 €
Field work	15.073 €
Lump sum for steering	10.460 €
Working time for m&r	9.926 €
Divers other costs	8.189 €
Suction vehicle	8.182 €
Material costs for m&r	6.234 €

The installation costs and the discounted costs of the three subcategories of the operating costs over the scheduled duration, and the resulting overall costs, are shown in the next table:

Year of erection of decontamination facility	2005
Scheduled duration of decontamination measuers [ys]	20
Installation costs [€]	2.709.556
Costs for supervision of the operations [€]	1.598.217
Costs for maintenance and repair [€]	303.360
Costs for measurement and control technology [€]	157.637
Overall costs [€]	4.768.771

The costs per contaminated volume for project A+B are approx. 31 €/m³.

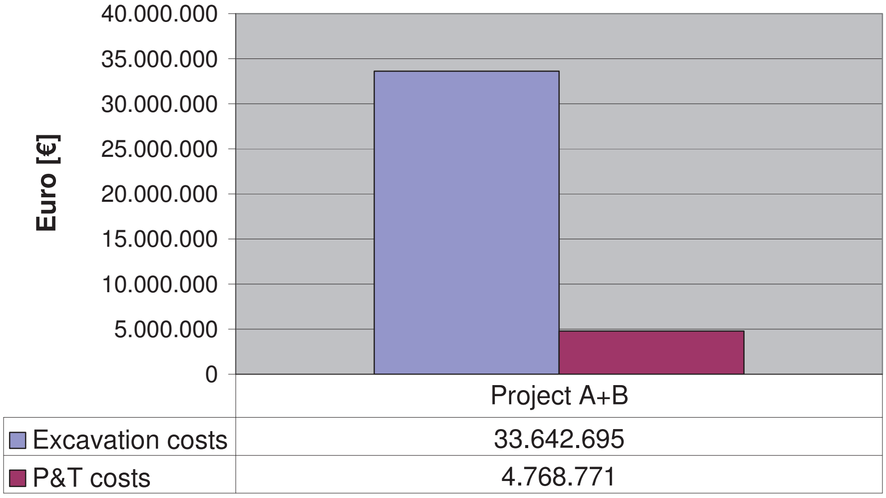
Predicted excavation costs for project A+B

The probability that the costs lie between the minimum costs and maximum costs is 90%.

	Minimum costs	Most likely costs	Maximum costs
Costs of excavation [€]	10.464.685	12.108.228	13.540.322
Costs for disposal [€]	16.836.658	18.476.040	20.179.854
Costs for planning, site supervision, construction site burden costs 10% [€]	2.730.134	3.058.427	3.372.018
Overall costs [€]	30.031.477	33.642.695	37.092.194

The costs per contaminated volume for the most likely case are approx. 200 €/m³.

Economic comparison of pump and treat and excavation for Project A+B



The costs for excavation and disposal are approx 7.1 times higher than the pump and treat costs for project A+B.

7.6.2 Pump and treat Project C – Con. Vol. 440.000 m³

Data for the extent of the contamination for the pump and treat project C is given in the next table:

Contaminated volume [m³]	440.000
Area fully contaminated [m²]	20.000
Area partly contaminated [m²]	110.000
Depth fully contaminated [m]	11
Height of the contamination plume [m]	2
There from clean coverage [m]	7

The next two tables give a detailed overview of the distribution of the installation and the operating costs for project C:

Project C	Installation Costs
Mounting of facility	480.000 €
Digging of trenches	400.000 €
Project Mgmt.	250.000 €
Pipes and associated excavation	230.000 €
Monitoring system	180.000 €
Start up of facility	170.000 €
Regulation of facility	150.000 €
Other installation costs	120.000€

Project C	Operating Costs
Current controls	61.201 €
Lab analysis	49.895 €
Working time for m&r	30.397 €
Field work	21.533 €
Work with authority	19.637 €
Divers other costs	14.765 €
Maintenance for electrical parts	14.362 €
Suction vehicle	8.182 €
Material costs for m&r	5.854 €

The installation costs and the discounted costs of the three subcategories of the operating costs over the scheduled duration, and the resulting overall costs, are shown in the next table:

Year of erection of decontamination facility	2005
Scheduled duration of decontamination measuers [ys]	30
Installation costs [€]	1.980.000
Costs for supervision of the operations [€]	2.432.948
Costs for maintenance and repair [€]	683.041
Costs for measurement and control technology [€]	355.509
Overall costs [€]	5.451.499

The costs per contaminated volume for project C are approx. 12 €/m³.

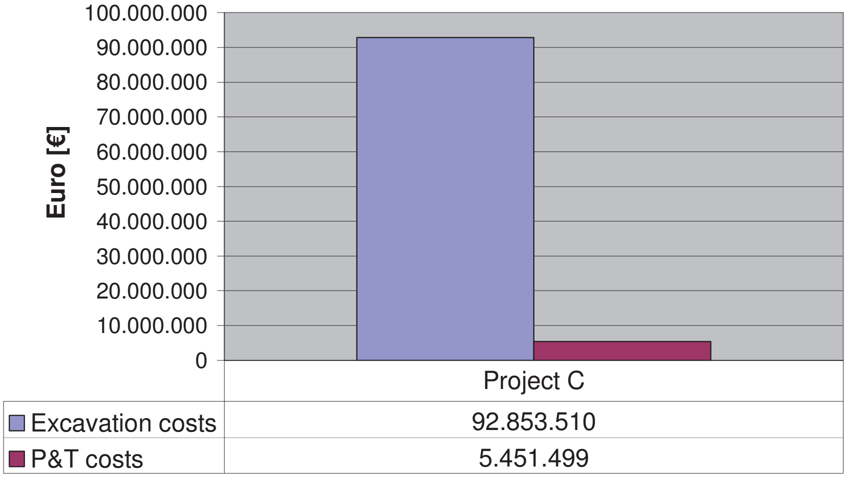
Predicted excavation costs for project C

The probability that the costs lie between the minimum costs and maximum costs is 90%.

	Minimum costs	Most likely costs	Maximum costs
Costs of excavation [€]	31.834.836	36.012.282	39.309.606
Costs for disposal [€]	45.960.000	48.400.000	50.930.000
Costs for planning, site supervision, construction site burden costs 10% [€]	7.779.484	8.441.228	9.023.961
Overall costs [€]	85.574.320	92.853.510	99.263.567

The costs per contaminated volume for the most likely case are approx. 211 €/m³.

Economic comparison of pump and treat and excavation for Project C



The costs for excavation and disposal are approx. 17 times higher than the pump and treat costs for project C.

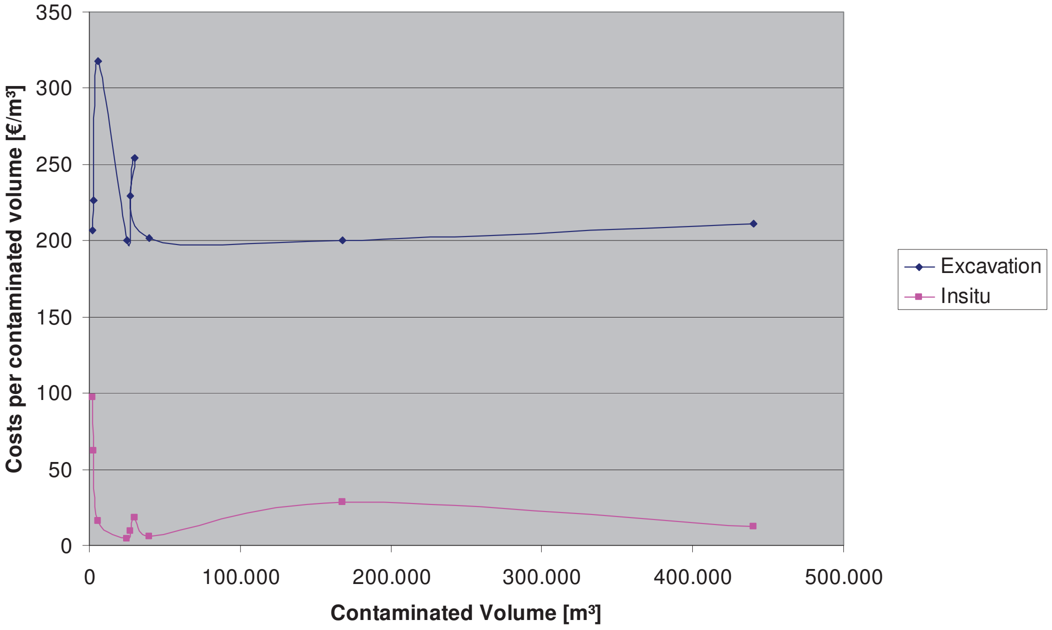
7.7 Findings of cost comparison between excavation and insitu projects

The next table and figure compare the costs per contaminated volume [€/m³] for the insitu and excavation option for all of the investigated projects.

Table 22: Cost per contaminated volume for investigated projects

Projects	Excavation costs per contaminated volume [€/m³]	Discounted insitu costs per contaminated volume [€/m³]	How much more expensive is excavation over insitu?
Project J - Con. Vol. 2.100 m³	206.87	97.05	2.13
Project D - Con. Vol. 3.200 m³	226.31	61.82	3.66
Project I - Con. Vol. 6.000 m³	318.06	16.20	19.63
Project H - Con. Vol. 25.000 m³	200.06	4.29	46.65
Project E - Con. Vol. 27.000 m³	229.37	9.66	23.73
Project F - Con. Vol. 30.000 m³	254.42	18.53	13.73
Project G - Con. Vol. 40.000 m³	201.39	5.95	33.84
Project A+B - Con. Vol. 153.900 m³	200.43	28.41	7.05
Project C - Con. Vol. 440.000 m³	211.03	12.39	17.03

The points in the following figure represent the investigated projects. The sequence of the projects is the same as in the table above, starting with project J and ending with project C.



It can be noted that the excavation costs do not show high deviations if you look at the costs per contaminated volume. The average costs per contaminated volume for all of the investigated projects is 227.59 €/m³. The largest deviation from the average costs per contaminated volume is Project I with 318.06 €/m³. Project I is special, compared to the other projects, because the contamination is very deeply located and a large amount of material has to be partly sideways stored. As it can be seen in the figure above, the costs per contaminated volume, which accumulate for excavation, are not mainly dependent on the amount of contaminated volume. The depth of the contamination, the height of the groundwater table or the volume of clean coverage are factors which considerably affect the resulting excavation costs per contaminated volume. Generally, the degree of the contamination or the distance to the disposal facility, are also important factors which govern the costs per contaminated volume for excavation. But as already mentioned prior in this thesis, these factors have constant values (for all of the investigated projects) so they do not influence the costs per contaminated volume for the investigated projects in this thesis.

The costs per contaminated volume, for insitu projects, show very high deviations as it can be seen in the figure above. They are significantly higher for the two projects with the smallest contaminated volume compared to the other projects. The reason for the relatively low costs per contaminated volume for the third project (Project I) with small contaminated volume is that it is a monitoring project, where no active decontamination measures are carried out and as a result the overall costs which accumulate are much cheaper compared to the other two projects with small contaminated volume.

Generally, it has to be noted that there is a certain minimum of costs for insitu projects (such as the installation costs for the equipment and the operating costs for a certain time frame), independent of the amount of contaminated volume.

These minimum costs are of particular interest for projects with small contaminated volume; they are the reason for the relatively high costs per contaminated volume which accumulate for the two projects with the smallest contaminated volume.

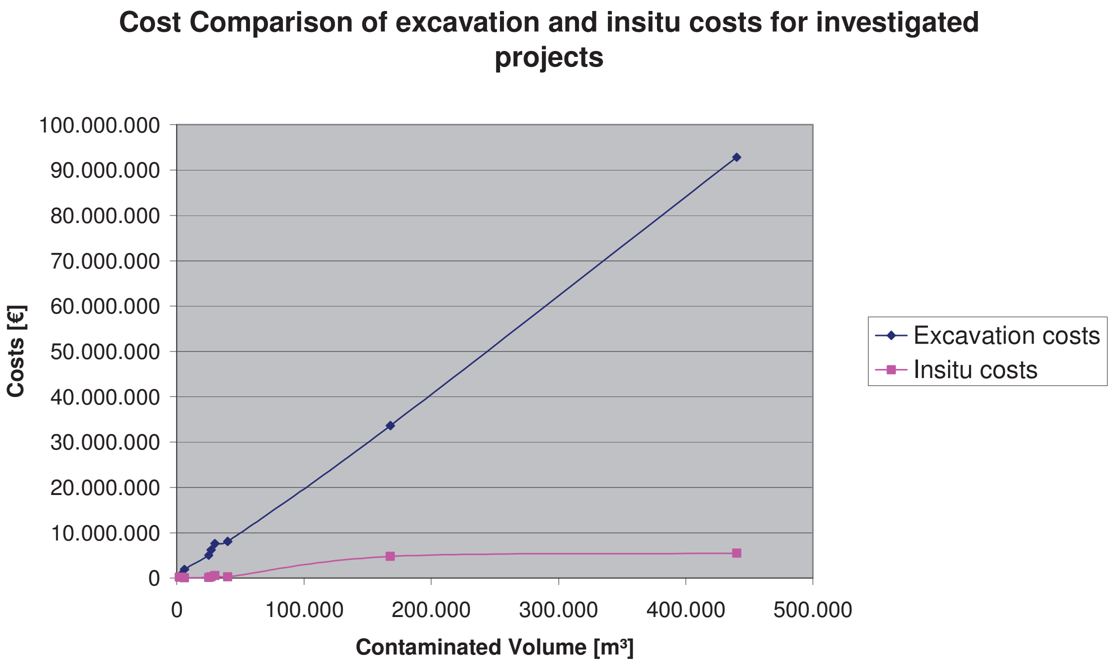
Concerning the projects with average and large contaminated volume it can be noted that the costs per contaminated volume also largely deviate (from 4.29 €/m^3 to 28.41 €/m^3). The reasons for these high deviations is that the costs per contaminated volume mainly depend on the specific circumstances that prevail at the contaminated site (such as the types of contaminants that are present in the subsurface, the hydro-geological conditions which prevail in the subsurface or the amount of groundwater that is being treated per year) and not the amount of contaminated volume.

The next table and the two following figures compare the absolute costs and the associated contaminated volume for excavation and the insitu option. The first figure shows the costs and associated contaminated volume for all nine projects whereas the second figure only shows the costs and associated contaminated volume for projects which have small contamination.

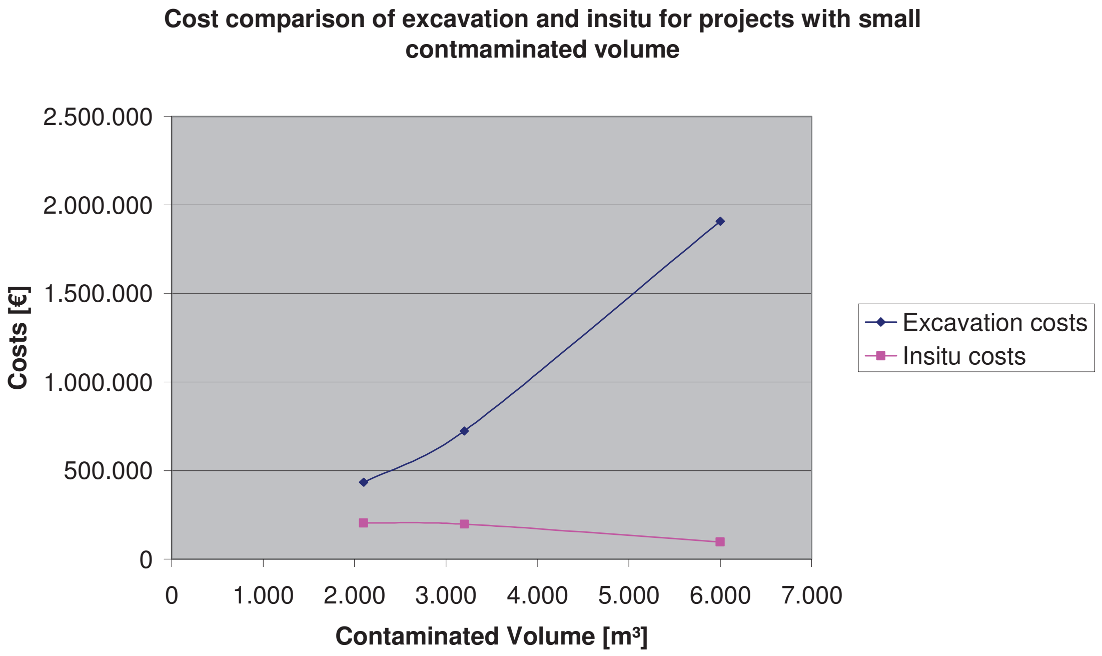
Table 23: Absolute costs for investigated projects

Projects	Absolute excavation costs [€]	Absolute discounted insitu costs [€]	Cost difference [€]
Project J - Con. Vol. 2.100 m^3	434.430	203.796	230.634
Project D - Con. Vol. 3.200 m^3	724.186	197.825	526.360
Project I - Con. Vol. 6.000 m^3	1.908.341	97.217	1.811.123
Project H - Con. Vol. 25.000 m^3	5.001.397	107.217	4.894.180
Project E - Con. Vol. 27.000 m^3	6.192.909	260.952	5.931.956
Project F - Con. Vol. 30.000 m^3	7.632.546	555.805	7.076.741
Project G - Con. Vol. 40.000 m^3	8.055.661	238.049	7.817.612
Project A+B - Con. Vol. 153.900 m^3	33.642.695	4.768.771	28.873.924
Project C - Con. Vol. 440.000 m^3	92.853.510	5.451.499	87.402.012

The points in the following figure represent the nine investigated projects. The sequence of the projects is the same as in the table above, starting with project J and ending with project C.



The next figure shows the three projects with small contaminated volume.



As shown in the figures above, the insitu option is cheaper than the excavation option for all of the investigated projects and the difference in absolute costs increases at a very high rate with ascending contaminated volume.

7.8 When is excavation viable from an economic point of view?

As it can be seen in the table above, for all of the investigated projects, the insitu option is considerably more economically than the excavation option. One of the goals of this thesis was to find out when excavation is economical, or in other words, at which volume can excavation be carried out so that the costs are comparable with insitu. Of course this question is difficult to answer because it is mainly dependent on many site specific factors. In order to get a rough idea how much contaminated volume can be excavated so that excavation remains viable/economical, I have investigated three of the projects (J, D, F) in detail, whereby two of the projects have small contaminated volume and one of the projects average contaminated volume. For these three projects, contaminated volumes for excavation (in the best, average and worst case) were examined in order to reach the predicted insitu costs of the projects. The best case means excavation at minimum costs, average case means excavation at most likely costs and worst case means excavation at maximum costs. For this purpose, all the input parameters for the simulation of the excavation costs have not been changed with the exception of the input parameter area partly contaminated.

The value of partly contaminated area has been adjusted (for the calculation of the excavation costs) in order to reach the predicted insitu costs of the investigated projects. All the other parameters for the three investigated projects have not been changed as it can be seen in the next tables.

Project J	Best case	Average case	Worst case
Contaminated volume [m³]	1.080	985	913
Area fully contaminated [m²]	0	0	0
Area partly contaminated [m²]	386	352	326
Depth fully contaminated [m]	4.8	4.8	4.8
Height of the contamination plume [m]	2.8	2.8	2.8
There from clean coverage [m]	2	2	2

Project D	Best case	Average case	Worst case
Contaminated volume [m³]	950	874	813
Area fully contaminated [m²]	0	0	0
Area partly contaminated [m²]	380	350	325
Depth fully contaminated [m]	6.5	6.5	6.5

Height of the contamination plume [m]	2.5	2.5	2.5
There from clean coverage [m]	4	4	4

Project F	Best case	Average case	Worst case
Contaminated volume [m³]	2381	2185	2010
Area fully contaminated [m²]	0	0	0
Area partly contaminated [m²]	2381	2185	2010
Depth fully contaminated [m]	4.5	4.5	4.5
Height of the contamination plume [m]	1	1	1
There from clean coverage [m]	3	3	3

The insitu costs for project J amount to 203.796 €, whereby 2.100 m³ contaminated material can be treated. 913 – 1.080 m³ contaminated material can be excavated for the same costs.

The insitu costs for project D amount to 197.825 €, whereby 3.200 m³ contaminated material can be treated. 813 – 950 m³ contaminated material can be excavated for the same costs.

With the assumption that there are constant insitu costs for project J and project D (that means that the insitu costs for project J remain constant for contaminated volumes of 2100 m³ or less and the insitu costs for project D remain constant for contaminated volumes of 3200 m³ or less), the conclusion can be drawn, that excavation might be a potential economic remediation option for project J if the contaminated volume is less than 1.080 m³ and for project D less than 950 m³.

Note: It can be noted that there are certain minimum costs (installation costs and the operating costs over a certain time frame) for insitu projects. However, there is simply not enough data available in order to obtain an idea of the amount of minimum costs for projects with small contaminated volume. This is the reason why this assumption (of the constant insitu costs) has been made because it is not clear how insitu costs behave with smaller contaminated volumes.

Of course this assumption does not account for the fact that the insitu option may be a cheaper option if less volume is contaminated. Nevertheless, insitu is the most economic remediation option for contaminated volumes exceeding 1.080 m³ under the same circumstances as for project J, and contaminated volumes exceeding 950 m³ under the same circumstances as for project D.

After examining both projects with small contaminated volumes, it can be seen that excavation provides an economic alternative to insitu for very small contaminated volumes to up to 1.080 m³. It should be noted though that 1.080 m³ is only a rough guideline because this value is strongly dependent on site specific circumstances.

The project with average contaminated volume (project F) was only investigated to point out, once again, the very significant cost discrepancy between insitu and excavation (for projects with average contaminated volume).

The insitu costs for project F amount to 555.805 €, whereby 30.000 m³ contaminated material can be treated. 2.010 – 2.381 m³ contaminated material can be excavated for the same costs. This only corresponds to 6% - 8% of the total contaminated volume.

7.9 Main cost causers of insitu projects

In the project description the breakdown of the operating and installation costs was provided separately for the investigated projects. The average cost distribution of the subcategories, within the installation and operating costs, has been examined in the following for pump and treat and monitoring projects. One of the goals of these investigations is to examine the main cost causers for the investigated remediation methods (cost causers show which particular subcategories largely contribute to the overall insitu costs). Another goal of these investigations is to analyse if the cost causers show a constant behaviour or whether they deviate significantly from project to project.

Some subcategories such as laboratory analysis have a quite similar cost structure for all of the investigated projects meaning that they contribute to a similar extent to the overall operating costs. Other subcategories, such as regulation of the decontamination facility, show high cost deviations for the investigated projects; that means that for some projects this subcategory is responsible for a very high portion of the installation costs whereas for other projects they contribute to a small extent to the installation costs.

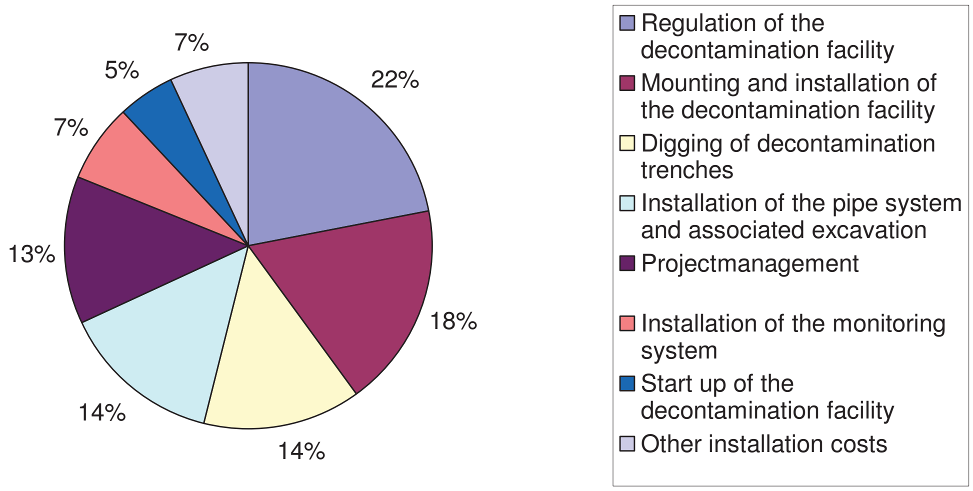
The reason for the following investigations is to provide the planners of future remediation projects with information on the cost causers and their behaviour (constant or deviating). The information, which subcategories contribute to a great extent to the overall costs, is of great importance for planners, because they can already try to reduce, if possible, these costs in the planning phase. The information which subcategories show a constant behaviour and which subcategories strongly deviate can be used by planners, in order to assess the overall costs and the associated risks in a more accurate way.

Note: The explanation of the subcategories is provided in Chapter 6.3 Allocation of insitu costs.

Pump and treat projects

The installation costs have been divided into different subcategories. The subcategories which are responsible for the highest proportion of the overall operating costs are shown separately in the next figure whereas the remaining installation costs are summarized under the subcategory other installation costs.

Average distribution of installation costs for investigated pump and treat projects



Data was available for the installation costs for seven pump and treat projects, the costs that apply for the subcategories within the installation costs will now be investigated in detail. Seven pump and treat projects can be investigated because the installation costs are separately available for project A and B, whereby the operating costs are summed up for both projects.

Regulation of the decontamination facility makes up (on average) 22% of the total installation costs. It is the largest cost causer for four of the projects, for those projects it is responsible for 25% - 35% of the total installation costs. On the other hand, the regulation of the decontamination facility is not a major cost causer for the three other projects. It is only responsible for 8% - 13% of the total installation costs. So, although the costs that accumulate for regulation of the decontamination facility are on average responsible for the highest portion of the installation costs they are deviating strongly.

Mounting and installation of the decontamination facility makes up (on average) 18% of the installation costs and represent the highest installation costs for three of the projects. Also for three other projects the mounting and installation of the decontamination facility cause a high portion of the total installation cost. However, for one project, the costs for mounting and installation of the decontamination facility are insignificantly small with 5%.

So, with the exception of one outlier, the mounting and installation of the decontamination facility contribute at a constant high amount to the overall installation costs.

The two subcategories, regulation of the decontamination facility and mounting and installation of the decontamination facility, are the main cost causers within the installation costs of the pump and treat projects. Together they are responsible for between 28% and 50% of the total installation costs, with an average of 39% for the seven investigated projects.

Installation of the pipe system and associated excavation makes up (on average) 14% of the installation costs. For three projects it causes the second largest costs and for one project, the third largest costs, responsible for between 14% - 26% of the total installation costs. For the other three projects the costs lie below the average value at 5% - 12%. The costs for installation of the pipe system and associated excavation strongly deviate.

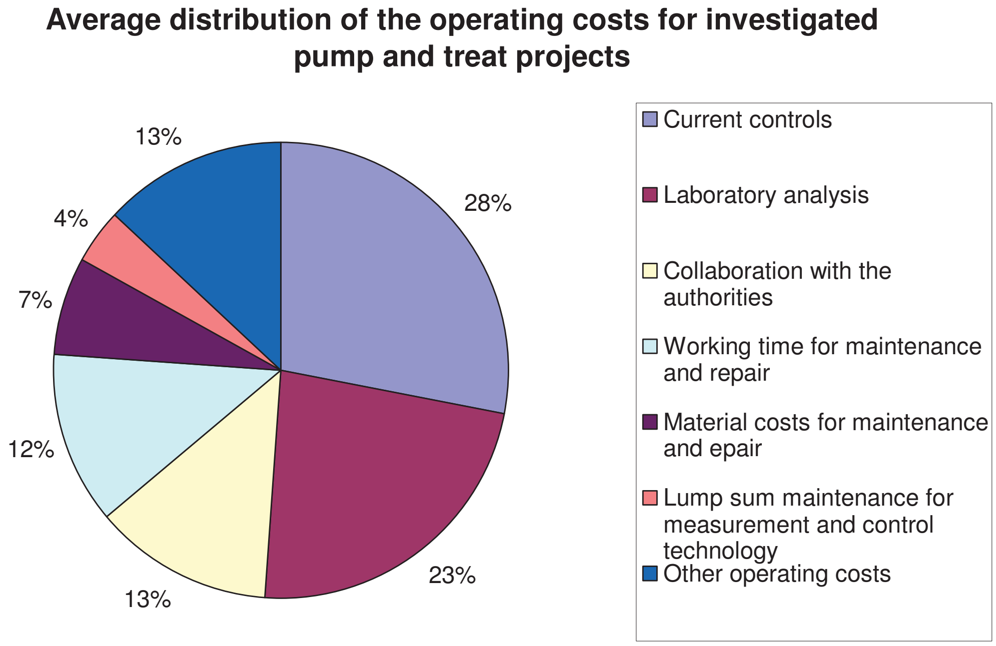
Digging of the decontamination trenches make up (on average) 14% of the installation costs for the seven investigated projects. An interesting fact is that for three projects where the installation of the pipe system and associated excavation were 5% - 12% below the average value, the costs that accumulated for digging of the decontamination trenches were higher than the average value, being responsible for 15% - 20% of the total installation costs. The costs for digging of the decontamination trenches also strongly deviate.

So the costs of the two subcategories, installation of the pipe system and associated excavation and digging of the decontamination trenches, are together responsible for between 21% and 34 % of the total installation costs with an average value of 28 %. Together these costs do not deviate.

Project management makes up between 10% and 17% of the total installation costs with an average value of 13%. It can be said that the costs that accumulate for project management contribute at a constant amount to the overall installation costs for all of the investigated projects.

Other installation costs make up (all together) 19% of the total installation costs, however the single subcategories that are summarized within the other installation costs do not contain major cost causers and therefore they will not be discussed further in detail.

The operating costs have been divided into different subcategories. The subcategories which are responsible for the highest proportion of the overall operating costs are shown separately in the next figure whereas the remaining operating costs are summarized under the subcategory other operating costs.



The operating costs were available for six pump and treat projects (which date from the year 2007). For five projects, the cost distribution within the subcategories of the operating costs is quite similar, whereas for one project (project D) the cost distribution is significantly different from the other projects. The reason for the abnormal cost distribution of project D is explained in the following:

The costs which accumulated for additional maintenance of the electrical parts of the decontamination facility are with 39% of the total operating costs very high compared to the average costs of 1% which accumulated for the other five projects.

This is the reason why the operating costs of the five pump and treat projects have been investigated, without considering project D, which exhibits an abnormal cost distribution compared to the other five projects.

For the five investigated pump and treat projects current controls make up (on average) 28% of the total operating costs and, for four of the projects this makes up the largest cost fraction, and for one project the third largest cost fraction.

Laboratory analyses make up (on average) 23% of the operating costs and are responsible for the second largest cost fraction for all of the investigated projects.

It can be concluded that the costs for current controls and laboratory analyses are the main cost causers for pump and treat projects. They contribute to the overall operating costs with a similar percentage. Together they make up between 41% and 68% of the overall operating costs, whereas the average is 51%. These two subcategories contribute to the overall operating costs at a constant amount.

The collaboration with the authorities makes up (on average) 13% of the operating costs. For one project it is responsible for 32%, making it the largest cost causer. The costs are significantly lower for the other projects, making up between 5% and 13% of the operating costs. 32% can be said to be an outlier, responsible for the relatively high value of the average costs of 13%. Apart from the outlier, it can be concluded that the operations concerning the collaboration with the authorities contribute to a constant amount to the overall operating costs.

The working time for maintenance and repair is (on average) responsible for 12% of the operating costs. For three projects, the costs barely deviate from the average value of 12% whereas for the other two projects the deviations were significant. For these two projects they were responsible for 6% and 19% of the total operating costs. Working time for maintenance and repair can said to be a subcategory which shows a moderate deviation within the cost structure of the investigated projects.

The material costs for maintenance and repair make up (on average) 7% of the total operating costs. An interesting fact is that the material costs do not show a correlation with the working time, meaning that high costs for working time do not necessarily also mean high material costs.

Lump sum maintenance of the electrical parts of the decontamination facility is (on average) responsible for 4% of the total operating costs, whereby either 5% or 6% accumulated for the investigated projects with one exception where no costs accumulated.

The other operating costs make up between 5% and 20% of the total operating costs with an average value of 13% for the investigated projects. It is important to note that there are nine subcategories summarized within the other operating costs and none of these subcategories contribute significantly to the total operating costs.

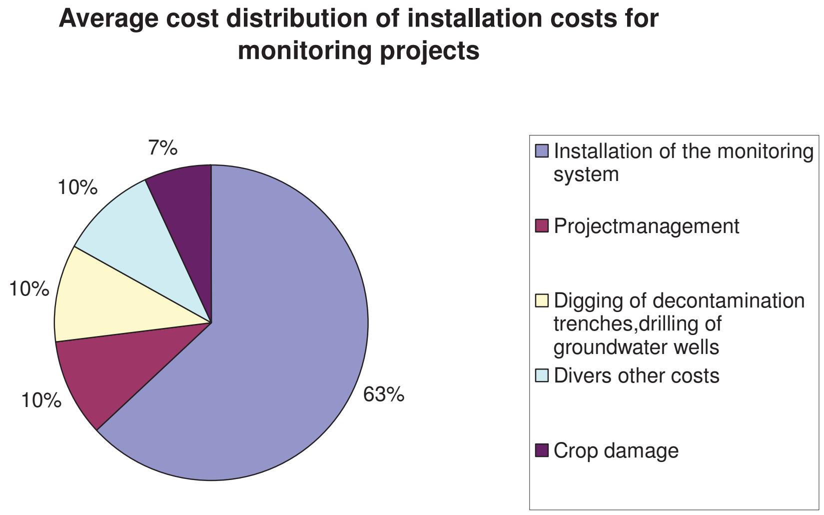
Conclusions for pump and treat projects

The investigated subcategories within the installation costs of the pump and treat project generally show a strongly deviating behaviour (especially the two main cost causers). The only exceptions are the subcategories Project management (constant behaviour), and mounting and installation of the decontamination facility (also constant behaviour with the exception of one outlier).

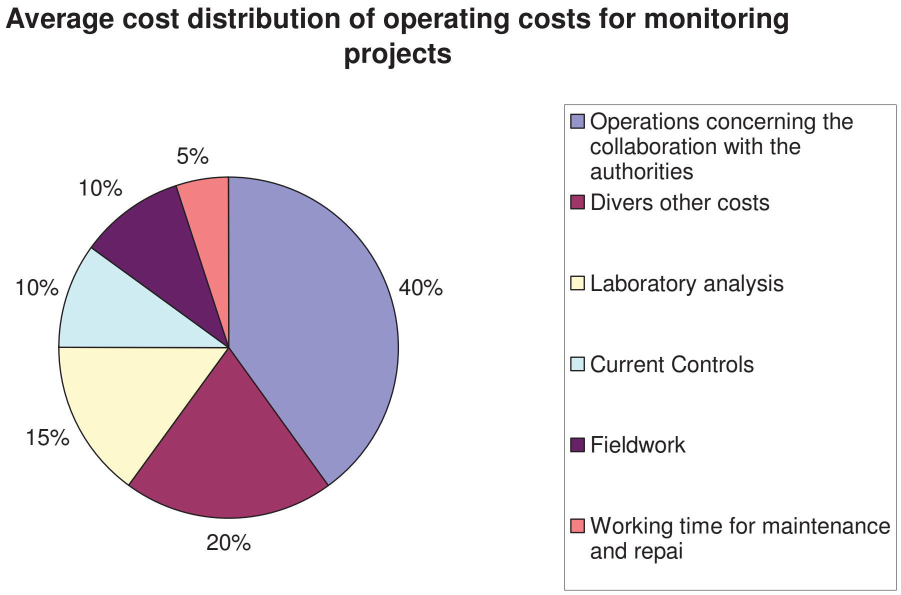
In contrast, the investigated subcategories of the operating costs generally show a constant behaviour (especially the two main cost causers laboratory analysis and current controls). The collaboration with the authorities also shows a constant behaviour with the exception of one outlier. Only working time for maintenance and repair shows moderate deviations.

Monitoring Projects

Data is available for two monitoring projects; the next figure gives an overview of the average cost structure of the subcategories within installation costs:



For both investigated monitoring projects, the installation of the monitoring system is responsible for an overwhelming part of the installation costs. For one project it is responsible for 60% and for the other project 67% of the total installation costs. So, the costs that accumulate for the installation of the monitoring system are on average responsible for the highest portion of the installation costs, they show a constant behaviour. Costs for crop damage and diverse other costs only contributed to a small extent to the overall installation costs for both projects. Costs for project management and drilling of groundwater wells only accumulated for either one of the two projects, so these costs deviate strongly.



For the investigated monitoring projects, collaboration with the authorities is the major cost causer, responsible for 40% of the overall operating costs for both projects, so they show a constant behaviour. Laboratory analyses contribute 10% of the operating costs for one project and 20% for other project. They show a moderate deviation.

Collaboration with the authorities and laboratory analyses are the only two subcategories within operating costs where costs for both projects accumulated. All the other subcategories (such as fieldwork, current controls, working time for maintenance and repair and diverse other costs) either accumulated for one of the two projects but not for both, those costs are deviating strongly for the two investigated projects

Conclusion for monitoring projects

It has to be noted that the data base for monitoring projects (two projects) is not as good as the data base for the pump and treat projects. Concerning the installation costs it can be noted that the only cost causer which accumulated for both of the projects is the installation of the monitoring system (which contributed to a constant amount for both of the projects). Concerning the operating costs it can be noted that collaboration with the authorities is the major cost causer for both of the investigated projects (which contributed a constant amount for both projects). The only other cost causer which accumulated for both projects is the laboratory analysis, it shows moderate deviation.

8 Summary and outlook

In the introduction of this thesis, it was noted that the first question which usually arises, once a contaminated site has been identified, is which remediaton method should be implemented for the remediation of the contaminated site. The following provides a summary of the most important results that were detected during the research undertaken in compiling this thesis. Generally, there are various remediation methods that are used throughout the world; they can be divided into remediation methods which have a long standing record in the industry, those which are being field tested and those which still have an experimental status. Remediation methods which are well established and have a long standing record in the field were particularly investigated in this thesis. Whereby it is important to note in this context, that new remediation methods are rapidly developing, and some methods which were tested at an experimental stage a few years ago are now becoming generally accepted within the industry and may show even better results concerning the attainable degree of purification, sustainability issues and associated costs than those with a long standing record. This thesis however focuses on those remediation methods with a long standing record in order to assess and analyse the current market situation. Although all investigated remediation methods have their strengths and weaknesses concerning their applicability for a contaminated site, the most important criterion for the selection of a remediation method, is the probability at which it is capable of fulfilling the regulatory requirements that are set from responsible authorities. Hence, the Heracles study was carried out in order to investigate the different screening values which were applied in the fifteen European countries which participated in this study. The conclusion of the study was that there are, among the participating countries, big deviations in screening values that have to be achieved in order to comply with the existing law. The main reason for the deviating screening values is the inclusion or exclusion of different receptors in the corresponding laws. Whereas human health is considered as a receptor in all of the investigated countries the inclusion or exclusion of other receptors (such as terrestrial ecosystems, groundwater or surface water) strongly varies in the participating countries. In many countries, including Austria, the screening values are under revision and there are ongoing discussions for the harmonisation of the different screening values within the EU. In Austria there are laws which govern the handling of contaminated sites such as the ALSAG, the Water Act or the Waste Management Act which can come into force depending on the specific circumstances of the contamination; however there is ongoing discussion in legal bodies to provide one administrative law which is responsible for the remediation of contaminated land.

Aside from the regulatory requirements and the costs of the remediation methods, there are also other key factors which have to be considered before choosing an appropriate remediation method for a contaminated site. Every remediation method has a specific effect during and after the remediation process especially concerning human health and safety, environment, land use and stakeholder concern. In the decision making process, these factors should also be assessed and weighted when analysing suitable remediation methods for a contaminated site. Of particular economic interest in this manner is planned land use after the remediation process has been completed. In urban areas where land prices are high, the degree to which the contaminated site can be remediated will have a significant impact on the value of the site. In order to assess the most economic remediation method for a contaminated site, the costs of suitable remediation methods and the corresponding gain in land use have to be considered. So, even if the costs for a remediation method (which fulfils the regulatory requirements with the same probability as another remediation method) are significantly higher, the gain in land value can make the costly remediation option more economical. The last part of the thesis dealt with an economic comparison of remediation methods; it focussed on the economic comparison of excavation and insitu methods and was carried out with data that was provided by OMV. The installation costs and the operating costs (which accumulated for one year) have been provided for nine insitu projects. The net present value of the overall insitu costs has been calculated for those nine projects. In order to compare the insitu costs for already existing projects with the excavation costs that would have accumulated instead, a program was developed for the calculation of excavation costs. The program can be used in excel alone or it can be expanded with a software tool which is named @risk. For the investigations which were carried out in this thesis, this program was used together with @risk which is based on the concept of Monte Carlo Simulation. It was necessary to use @risk in order to be able to assign certain probability distributions to the input parameter of the program. As a result of the calculations which were carried out in the program, the minimum, most likely and maximum costs (whereby the probability is 90% that the costs lie in the range of the minimum and maximum excavation costs) for the excavation projects were obtained. A big advantage of the program which has been developed is that it can also be used for the calculation of excavation costs for future projects. The most important results of the economic comparison appear to be the following: For all of the investigated projects the insitu option is considerably cheaper than the excavation option. The cost difference in absolute numbers between insitu and excavation rapidly increases with increasing contaminated volume starting with about 530.000 € for small contaminated volume (2.100 m^3) to 87.400.000 € for large contaminated volume (440.000 m^3). The cost difference between insitu and excavation can be said to behave almost exponential with ascending contaminated volume for the investigated projects. One of the goals of this thesis was to find out at which contaminated volume excavation can be carried out so that the costs can be comparable with insitu. In order to find that boarder three of the projects have been investigated in detail. Furthermore the subcategories within the installation and the operating costs, for pump and treat and monitoring projects have been examined. The main cost causers and their behaviour (constant or deviating) has been investigated. Concluding it can be noted that the main difference between an insitu method and excavation is the following: If an insitu method is applied at a contaminated site there is always a risk of failing the legal requirements concerning the screening values that need to be achieved; and even if a site has been decontaminated successfully, there is still a risk that after some time the responsible authorities may regulate advanced decontamination measures. This particular risk does not exist if excavation is applied instead if insitu. Therefore, this risk has to be weighed up with the costs before a decision can be made regarding insitu or excavation at a contaminated site. Whereby it has to be noted, strictly from an economic point of view and based on the data that was provided by OMV, there is a very high probability that insitu is cheaper than excavation even for projects with small contaminated volume (such as it could be investigated for the three projects which were categorised under “small contaminated volumes”).

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