INSTITUT FÜR NACHHALTIGE ABFALLWIRTSCHAFT UND ENTSORGUNGSTECHNIK
Montanuniversität Leoben
Peter-Tunner-Straße 15
www.unileoben.ac.at/iae
A-8700 Leoben
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Dissertation

A knowledge-based system for contaminated sites management

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Vorgelegt von:
Dipl.-Ing. Alberto Bezama
0135209

Betreuer:
O.Univ.Prof.Dipl.-Ing.Dr.techn. Karl E. Lorber

Gutachter:
O.Univ.Prof.Dipl.-Ing.Dr.techn. Karl E. Lorber
O.Univ.Prof.Dipl.-Ing.Dr.mont. Jürgen Wolfbauer

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EIDESSTATTLICHE ERKLÄRUNG

Ich erkläre an Eides statt, dass ich die vorliegende Dissertation selbständig und ohne fremde Hilfe verfasst, andere als die angegebenen Quellen und Hilfsmittel nicht benutzt und die den benutzten Quellen wörtlich und inhaltlich entnommenen Stellen als solche erkenntlich gemacht habe.

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Kurzfassung

Ein wissensbasiertes System für Altlastenmanagement

Die vorliegende Arbeit stellt die Entwicklung eines dreistufigen Decision Support Systems vor, welches dem Management bei Entscheidungen über Sicherung und Sanierung von Altlasten behilflich sein soll.

Basierend auf vorhergehenden Modellen, liefert der erste Schritt des Systems ein Risikoanalyseverfahren zur Kennzeichnung und Einstufung von Verdachtsflächen. Im zweiten Schritt werden technisch geeignete Sanierungskonzepte mit Hilfe eines Fuzzy-Logic basierten Entscheidungsmodell für jene gefahrdrohende Verdachtsflächen, die im ersten Schritt als solche gekennzeichnet wurden, entwickelt. Die Entwicklung dieses Arbeitsschrittes berücksichtigt die Charakterisierung der Kontamination und der hydrogeologischen Gegebenheiten der Verdachtsflächen, sowie die Risikoanalyse und die voraussehbare Wiedernutzung der Altlasten. Im dritten und abschließenden Schritt des Systems wird auf der Basis einer Balanced Scorecard, welche mit Hilfe eines Logical Framework Approach aufgebaut wurde, die passendste Technologie für das Altlastenmanagement ausgesucht. Ein wichtiger Aspekt dieses letzten Schrittes ist die Einbindung der Ansichten aller in das Projekt teilnehmenden Interessenvertreter in dem Evaluierungsprozess, was letztendlich ein umfassendes Entscheidungswerkzeug erst ermöglicht.

Aufgrund seines Designs und seiner Durchführung kann das entwickelte System als Werkzeug für Know-how Transfer für Entwicklungsländer verwendet werden, die sich erst am Anfang der Auseinandersetzung mit dem Altlastenproblem befinden, obgleich das System ursprünglich auf der Basis der österreichischen und deutschen Erfahrungen und Verhältnisse konzipiert und validiert wurde. Das System wurde in Zusammenarbeit mit der Umweltkommission Chiles zur ersten landesweiten Erfassung von Verdachtsflächen in der VIII. Region eingesetzt. Dieses Projekt verfolgt das Ziel, eine Kennzeichnung und Risikoevaluierung von Verdachtsflächen in den anfälligsten Zonen der am meisten industrialisierten Region Chiles durchzuführen. Die Ergebnisse dieses Kataster werden genaue Informationen über die Dimension des Altlastenproblem übermitteln, welche für die Diskussionen über die bevorstehende Entwicklung umweltrechtlicher Rahmenbedingungen von Altlasten in Chile benötig werden.

Abschließend werden in der vorliegenden Arbeit, unter Betrachtung der in der VIII. Region identifizierten Verdachtsflächen, jene nötige Maßnahmen für die künftige Implementierung des entwickelten wissensbasierten Systems in Chile vorgeschlagen. Weiters, werden die erforderlichen Schritte diskutiert, welche für die Adaptierung europäischer Sicherungs- und Sanierungstechnologien für Chile benötigt werden.

Abstract

A knowledge-based system for contaminated sites management

The present work introduces the development of a three-step decision support system for helping management to decide in contaminated sites remedial projects.

Based on previous models, the first step of the system provides a risk assessment procedure to identify and classify sites suspected of contamination. A second step deals with the identification of the technically suitable remedial options for each risk-posing site identified in the first step through the use of a fuzzy-logic decision module. The development of this procedure has considered the characterization of the pollution and the hydro-geological conditions of the sites as well as the risk assessment evaluation and the foreseen redevelopment of the site. The third and final step of the system suggests the most appropriate technology for the management of the contaminated sites through the utilization of a Balanced Scorecard constructed for this purpose by following a Logical Framework Approach. An important aspect of this last step is the introduction into the evaluation of all points of view from the entities participating as project stakeholders, which determines henceforth a more integral decision-support tool.

Due to its design and realization, and although constructed and validated according to the Austrian and German experiences, the developed system can be utilized as a know-how transfer tool for developing countries that are starting to deal with the contaminated sites problem. The system has been used in cooperation with the Chilean National Environmental Commission in the first land register of potentially contaminated sites in the Region of the Bio Bio. This project aims to the identification and risk evaluation of potentially contaminated sites within the vulnerable areas of the most industrialized Region of Chile. The results of this land register will provide with the knowledge on the dimension of the contaminated sites problem needed for the discussion on the forthcoming development of the legal framework regarding contaminated sites in Chile.

Finally, considering the identified contaminated sites situation in the Region of the Bio Bio, the activities needed for a future application of the knowledge-based tool in Chile are introduced, as well as the steps to follow for an adaptation of the state-of-the-art remedial technologies from the European experience to the Chilean situation.

“No man is an island, entire of itself,
every man is a piece of the continent, a part of the main”

John Donne (1624).
“Devotions Upon Emergent Occasions”
Meditation XVII: Nunc lento sonitu dicunt, Morieris.

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Executive Summary

Contaminated sites have been recognized as potential threats to the human health and the environment, as their impacts on water, soil and air media as well as their interrelations can provoke direct effects on the human health. For over a decade, the contaminated sites problem has been addressed by European countries, which has derived in the development of several technologies for managing both polluted soils and groundwater. This development has not only been driven by health and environmental aspects, but also because of economic pressures, as the remediation and redevelopment of derelict areas (i.e., “brownfields”) can be a meaningful alternative to undeveloped areas (i.e., “greenfields”) for the establishment of new industrial, recreational, housing and service locations.

In most developing countries, however, the subject of contaminated sites is a new environmental issue that authorities have recently started to deal with. Among these countries, Chile has just started to prepare the country's legal context as well as to foster the formation of research and investigation groups that will deal with the exploration, investigation and management of contaminated sites. That requires a comprehensive technical, scientific and legal support in this stage.

This work introduces a knowledge-based system for supporting decisions on contaminated sites management. Such support is accomplished by prioritizing the sites under suspicion of contamination in terms of their urgency for remedial actions and by suggesting the most appropriate course for actions (temporal containment and/or immediate remediation measures) to be taken for the priority sites. Hence, the system represents a comprehensive tool that allows the best use of limited financial resources (especially in developing countries) by focusing primarily on the sites that actually require immediate management measures. A further aspect of this work is the mutual cooperation with Chilean institutions to support the development of the Chilean Norms for contaminated sites, by cooperating in the development of the evaluation and management strategies at a national level, and the tutorial of the first evaluation process for identifying and primarily evaluating suspected contaminated areas in an industrial Region.

The first section of this Ph.D.-Thesis introduces the framework to which contaminated sites management projects are subjected. A summary of the legal context in Austria is presented, introducing the definitions and regulations related to contaminated sites that form the basis for this study. The technological alternatives for managing contaminated sites have been summarized and evaluated in a state-of-the-art review of identification and assessment procedures for sites under suspicion of contamination, as well as technologies for the containment, remediation and redevelopment of contaminated sites. Finally, the decision making theory has been introduced.

After providing the description of all aspects that must be considered in site remediation projects, the second section of this Ph.D.-Thesis introduces the development of a knowledge-based tool for the management of contaminated sites. The proposed tool entails

the development of a three-step system for the determination of the most appropriate technological alternative. The first section of the system aims to the evaluation of risks associated to each site, in order to identify the cases requiring remediation in the most urgent manner. A first risk assessment procedure, based on the EVAPASSOLD model, intends to identify and classify sites suspected of contamination by analysing the activity that has taken place in the site, its associated material danger, and the local conditions as well as the historical background of the site that may be collected. A second risk evaluation step, based on the Baden-Württemberg (B-W) evaluation process, is performed to determine more accurately the management process that should be addressed for each site suspected of contamination. The B-W process contemplates five different site classes, each of them suggesting different appropriate measures to be taken.

The second step of the system is intended to identify suitable remediation technologies to manage the contaminated site. In this step, the following conditions are considered in the evaluation: present pollutants (according to the following groups: Hydrocarbons, Mineral Oil, Halogenated hydrocarbons, PAHs, BTEX, Heavy metals), concentration of the pollution in the contaminated goods, extension and dispersion of the pollution (identification of the contaminated environmental goods), hydrogeological conditions of the location to characterize the soil (depths of cover layer, zone of aeration, saturation zone, bedrock, and further characterized by soil type, clay and organic content, permeability) and groundwater (groundwater layer depth, velocity, direction), the result of the risk assessment procedure and the intended future reuse of the site. The system first associates the present pollutants and their concentrations in soil and groundwater and, according to the experience in Europe and the U.S.A., selects the groups of clean up technologies (i.e., biological, physical, and chemical) that suit such conditions (or that have been largely demonstrated to work). There are some knock-out conditions to determine the feasibility of in-situ technologies according to the soil and pollutants characteristics. Further knock-out conditions are established by the geological and hydro-geological conditions of the site. Subsequently, the evaluation considers the results of the risk assessment process in order to determine the duration in which the remediation of the site should be accomplished. Moreover, the intended future reuse determines the maximal allowable level of contamination in the site for its future use, therefore establishing the necessary level of pollutants degradation/removal from the contaminated good, thus bringing a further evaluation on the technical feasibility of the remediation alternatives. Moreover, at this point, an estimation of the incurred time for remediation can be determined (especially in the case of biodegradation technologies). For an adequate evaluation of the suitable technologies, the total project costs have been calculated and embedded in the system. As result of this study stands a list of technologies that have been found suitable for the management of the evaluated site. This list of alternative technologies serves as the input for the final step of the knowledge-based system, the comparative evaluation process.

The third and final step of the developed system corresponds to a comparative evaluation of the identified technologies in a Balanced Scorecard (BSC). This BSC has been formulated through a modified logical framework approach, conducting the identification and analysis of the stakeholders, problems and objectives associated with soil and groundwater remedial projects, as well as their financial goals and limitations, and the ambitions of stakeholders in relation to site use options and environmental quality. From this analysis, the main goal of the remediation of contaminated sites has been broken down into a hierarchy of sub-goals until a level where, for the bottom elements, the scores of the goal achievements can be measured as relevant indicators. The graphical representation of the hierarchy of all sub-goals, bottom goals as measurable indicators is represented by an objective tree for contaminated sites remedial projects. For each indicator, a utility function has been built in order to transform the indicator scores into normalized utilities which can be aggregated upstream to verify the total utility scores of the remediation strategies and technologies. The definition of the comparative evaluation system is finished with the quantification of the relative importance of the goals within the objective tree levels. Taking into account the opinion of the identified stakeholders involved in the process, the importance of each goal of the evaluation system is weighted in order to determine their relative importance in the consolidated BSC. Through the utilization of the developed BSC, it is then possible to evaluate the identified technically-suitable technologies from the second step of the system, and suggest the most appropriate technology for the management of the contaminated sites according to the evaluation of all points of view from all entities participating as project stakeholders, which determines henceforth a more integral decision-support tool. This tool set is checked in its formulation and application against an export benchmark of important remediation projects at an Austrian national level.

The developed procedures and methods that form the knowledge-based tool have been considered as the starting point for the identification and evaluation of the contaminated sites in the Region of the Bio Bio, Chile, characterized by highly developed economic, industrial and cultural sectors, which makes it the second most important Region of Chile, after the Metropolitan Region of Santiago.

Through the conducted experiences in the framework of this Ph.D.-Thesis it was possible to establish the first land register process for the Region of the Bio Bio, aiming to obtain an overview of the actual contaminated sites situation in the Region and an approximate endangerment classification of the sites under suspicion of contamination located in the most vulnerable areas. Finally, considering the identified contaminated sites situation in the Region of the Bio Bio, this chapter presents the activities needed for a future application of the knowledge-based tool in Chile, as well as the basics of a potential technology and know-how transfer process regarding the adaptation of the environmental regulations and the state-of-the-art site management technologies from the European experience (introduced in the previous sections) to the Chilean situation.

1 Introduction

Soil has always been connected to the human development, as man's natural habitat and basis for their agriculture. Nevertheless, the traditional definition of soil (**"*upper layer of earth that may be dug or plowed and in which plants grow*"**[1]) does not really include the relationship between humans and soils. As a matter of fact, despite its importance in human life, the relationship between soils and human health has been undervalued until recently [1],[2],[3]. Currently, a holistic approach has been incorporated for the search of the best practices in soil science. This approach is defined as *"the task of all people concerned with the soil to direct their interest, not just towards the physical, chemical, and biological aspects, but also to those environmental, economic, social, legal, and technical aspects that affect soil use"* [4],[5].

The awareness of this interrelation has lead to a series of investigation lines and specialization areas, ranging from the economical [7],[8] and technical [9],[10] points of view to the social [11],[12], environmental [13],[14] and legal perspectives [15],[16],[17]. This series of specialization areas and different perspectives thus come all together when dealing with contaminated sites [18],[19],[20].

In the European Union (EU), as well as in most developed countries, contaminated sites have been recognized as potential threats to the human health [6],[21]. Such danger can be of different kinds, as their influences on water (e.g. drinking water resources), soil and air media and their interrelations can provoke direct effects on the human health [1],[21]. Considering these potential public health problems, contaminated sites have become an important issue for all industrialized countries.

Moreover, economic expansion and industrial growth are linked with growing lack of greenfields. The supply of new building sites is limited and must contend with other competing uses, such as housing, recreation, nature, traffic, agriculture, etc [22],[23]. Thus, the clean-up and reuse of former contaminated sites can be a meaningful alternative to address this issue, as most contaminated sites are located in metropolitan centers and are, therefore, prime candidates for urban development [24],[25].

1.1 Problem description

Contaminated sites negatively impact their surroundings. Therefore, their management brings a reduction of the community health risks [23],[26]. However, the selection of the best site contaminant containment and/or remediation technology is not a trivial task, especially considering the current proliferation of technologies for managing both polluted sites and

[1] Definition according to Merriam-Webster (Ed.) (2003): "Merriam-Webster's Collegiate Dictionary". 11th edition. Ed. Merrian-Webster. ISBN: 0877798087. Springfield, MA, U.S.A.

groundwater [9],[27],[28]. Moreover, site redevelopment has also been incorporated as an important process variable for the decision on the site management, adding a further technological/economic aspect to the proposed strategy [29].

Finally, the fact that soil remediation is a difficult task with very high costs must not be overlooked: the European Environment Agency (EEA) has estimated the total cost of the clean-up of contaminated sites in the EU to be between EUR 59 and 109 billion [30],[31]. Therefore, a coordinating concept for establishing a certain degree of consistency in optimized contaminated site management decisions is needed.

In most South American countries, the subject of contaminated sites is a new environmental issue that authorities have just started to deal with. There are cases like the region of Sao Paulo (Brazil), in which the subject has already been developed, and norms and regulations are already at hand. In such cases, a strong know-how exchange has been provided from industrialized countries to accelerate the adaptation of the existing regulations and norms to the reality of the region, as well as the subsequently implementation of the local legal framework [32].

The case of Chile presents currently an interested environmental-normative body that has started to prepare the country's legal context as well as to foster the formation of research and investigation groups that will deal with the exploration, investigation and management of contaminated sites at regional as well as national levels [33],[34]. New regulations have been just started to form the new legal framework in which the management activities for contaminated sites will take place. There is therefore the need of a comprehensive technical and legal support in this stage.

1.2 Objectives and goals

Considering the many alternatives available for the management of contaminated sites, it is clear that a decision support tool is needed. Despite the apparent need for and the usefulness of a knowledge-based system in contaminated site management, to date very little progress has been made in establishing these systems as viable tools in this area. Therefore, this work deals with the development of a knowledge-based system for supporting decisions on contaminated sites management based on the Austrian and European experience. This system will provide authorities and stakeholders with a comprehensive and robust tool for reducing the time and cost expenses in such decision-making activities.

A further aspect of this work is the mutual cooperation with Chilean institutions to help in the development of the Chilean Norms in the area of contaminated sites, to cooperate in the development of evaluation and management strategies at a national level, and the tutorial of the first evaluation process for identifying suspected contaminated areas in an industrial Chilean region.

The following goals are envisaged in this work:

- To implement a simplified risk assessment procedure based on the current state-of-the-art processes.
- To develop a strategy model for the selection of the management measures for industrial contaminated sites based on legal, economic, technical and social parameters.
- To implement a decision support tool in the form of an expert system for managing industrial contaminated sites.
- To promote a knowledge transfer to Chile, based on the information on social, legal, technical and economic aspects of the contaminated sites management in Austria to help in the development of the new national standards and regulations.
- To perform the first industrial suspected contaminated sites inventory (i.e., Catastro de Sitios Potencialmente Contaminados) in a selected industrial region of Chile.
- To perform a first and second risk assessment procedures for the suspected contaminated sites of a selected industrial region in Chile.
- To validate the decision support tool by performing a first management decision support in a selected industrial region of Chile.

2 Theoretical background

As described in Chapter 1 a series of investigation lines and study areas have been developed for define the key issues influencing the management of contaminated sites; among them, legal, technical, environmental, economic and social points of view have been identified as the most important aspects to consider when planning the management of derelict lands. Chapter 1 then introduces the main goals of this work, which are the development of a knowledge-based tool for helping in management decisions for contaminated sites, and the introduction and adaptation of this system to the Chilean reality.

Considering this, Chapter 2 presents an overview of the legal framework for contaminated sites, mainly considering the Austrian legislation as basis for the developed system. Chapter 2 examines the contaminated sites situation in Europe and the state-of-the-art methodologies and technologies for their investigation, evaluation and management. Finally, this chapter introduces the basics of decision theory.

2.1 Legal context for contaminated sites

In this section, the Austrian legal framework for the management of contaminated sites is introduced as basis for the following work. The legal framework for contaminated sites in Chile is still under development. Nevertheless, CONAMA (Chilean Environmental Commission) is currently working on determining on which extent the dimension of the contaminated sites problem actually impacts the human health and the environment on a national basis. It must be stated that one of the goals of this Ph.D. work is to help in the identification of suspected areas as well as the ranking of them, in order to provide with the dimension and characteristics of the risk-posing contaminated sites in Chile. A comprehensive legal context for Austria, Europe and Chile is presented in detail in Annex I.

2.1.1 Austrian definitions, norms and regulations

According to the Austrian law [35], the following definitions regarding the management of contaminated sites are stated:

Contaminated Site: Abandoned landfills („Altablagerungen“), and old industrial sites („Altstandorte“), which pose a considerable risk to the environment or to human health.

On-site: Treatment of materials from contaminated sites at the location (locally), directly within the limits of the site.

In-situ: Treatment of materials in contaminated sites without changing their spatial position.

Ex-situ: Treatment of materials from contaminated sites after excavation.

Off-site: Treatment of materials from contaminated sites after excavation at a place outside the limits of the site.

Containment: Prevention of the propagation of possible emissions of pollutants hazardous to health and environment. Containment does not eliminate the source of contamination.

Remediation: Removal of the endangerment cause and its effects in a contaminated site. With remediation measures the pollutants are either removed or transferred into an innocuous form.

Process combinations: The combination of the possible remediation and containment processes is possible. In fact, in some cases, the proper combination of process is the only way to achieve the desired remediation goal. The selection of the appropriate process(es) must be decided according to each individual case. The application of the selected processes can be performed in parallel or separately, in either spatial or time process steps. The following list presents examples of process combinations:

- Surface sealing, lateral sealing, hydraulic measures, active degassing,
- Excavation, material sorting and further separated treatment,
- Hydraulic process and soil vapor extraction,
- Immobilization and landfilling,
- Lateral sealing and microbiological treatment.

A summary of the most important, contaminated sites-related regulations in Austria is presented hereafter. For an overview of the current Austrian legal framework regarding contaminated sites, please refer to Table 1.

Water act: This act represents the most important fundamentals for inducing security measures and remediation of contaminated sites. Through the water act it is possible to obtain important aspects regarding the identification and investigation of contaminated sites. In the sense of the general concern for keeping waters clean and free of pollution, particularly groundwater, it states the water-legal grants that are necessary for impacts that impair the water conditions.

Landfill ordinance: This ordinance regulates the conversion of the goals and principles for the establishment of the state-of-the-art equipment and modus operandi for the deposit of wastes in landfills, in accordance with the waste management act as well as by protecting the public interest.

Law for the clean-up of contaminated sites: Law for the regulation of subventions for the remediation of contaminated sites. It contains aspects of the identification, investigation and evaluation of (suspected) contaminated sites.

Law for the promotion of environmental measures: Promotion of measures for the protection of the environment (e.g. within the framework of contaminated sites management).

Waste management act: Imposes measures for the harmless treatment of wastes and for the soils contaminated by them.

Table 1: Overview of the Austrian laws and norms regarding contaminated sites

Acronym	Name (*original German name*)
WRG	Water act (*Wasserrechtsgesetz 1959, last amended in BGBl. I Nr. 87/2005*)
DVO	Landfill ordinance (*Deponieverordnung BGBl. 164-1996, last amended in BGBl. II, 49-2004*)
ALSAG	Law for the clean-up of contaminated sites (*Altlastensanierungsgesetz – ALSAG. BGBl. Nr. 299/1989 as amended on BGBl. I Nr. 71/2003*)
UFG	Law for the promotion of environmental measures (*Umweltförderungsgesetz. BGBl. Nr. 185/1993 as amended on BGBl BGBl. I Nr. 71/2003*)
AWG	Waste management act (*Abfallwirtschaftsgesetz BGBl. I Nr. 102/2002*)
ÖNORM S 2085	Contaminated sites – Course of actions for treatment of waste deposits and industrial sites (*Altlasten – Ablauf zur Bearbeitung von Altablagerungen und Altstandorten*)
ÖNORM S 2086	Contaminated sites - Terms and definitions (*Altlasten – Benennung und Definitionen*)
ÖNORM S 2087	Contaminated sites – Identification and investigation of (suspected) contaminated sites (*Altlasten – Erhebung und Untersuchung von Verdachtsflächen und Altlasten*)
ÖNORM S 2088-1	Contaminated sites – Risk assessment concerning the pollution of groundwater which is to be safeguarded (*Altlasten – Gefährdungsabschätzung für das Schutzgut Grundwasser*)
ÖNORM S 2088-2	Contaminated sites – Risk assessment for polluted soil concerning impacts on surface environments (*Altlasten – Gefährdungsabschätzung für das Schutzgut Boden*)
ÖNORM S 2088-3	Contaminated sites – Part 3: Risk assessment for public asset air which is to be safeguarded (*Altlasten – Gefährdungsabschätzung für das Schutzgut Luft*)
ÖNORM S 2089	Contaminated sites – Security measures and remediation (*Altlasten – Sicherung und Sanierung*)
ÖNORM B 4452	Geotechnical engineering/foundation engineering - Cut-off walls (*Planung, Ausführung und Prüfung von Dichtwänden im Untergrund*)

2.2 The contaminated sites situation in Europe

From an European point of view, the main soil-associated problems are irreversible soil loss due to increased *soil sealing*, *soil erosion* and continuing deterioration due to *local* and *diffuse contamination*. Soil sealing refers to urbanization and infrastructure constructions; soil erosion is caused mainly by the action of water and, to a lesser extent, wind; local contamination refers principally to industrial activities and waste disposal contamination. The term “diffuse contamination” is used to describe the pollution produced from contaminated water flowing over soil, from eroded soil that pollutes surface waters, and from the leaching of contaminants through the soil that pollutes groundwater streams [31]. The occurrence and distribution of soil problems are influenced by the diversity, distribution and specific vulnerability of soils across Europe, coupled with physical aspects such as geology, relief and climate. A further factor is the distribution of driving forces across the continent [30]. The following summary intends to describe the general situation of the European soil problem, according to the latest studies of the European Environmental Agency (EEA) [31].

a) Western Europe: Soil contamination remains a problem in Western Europe (WE) despite several national and international initiatives that have been set up during the past 10 years to reduce air emissions and control, for example, the application of sewage sludge and the use of landfill for waste disposal. WE is highly urbanised (built-up areas occupy 15 % of its territory) and competition for the limited land available results in the loss or degradation of soil resources and in particular the sealing of the soil surface at unsustainable rates, for example through urban development and the construction of transport infrastructures.

b) Central and Eastern Europe: Soil degradation problems in the Central and Eastern European (CEE) countries are similar to those in WE, although there is less soil sealing. Most of the problems are inherited from the time of the former USSR, when environmental issues were of minor concern. Erosion is the most widespread form of soil degradation, linked to agricultural mismanagement and deforestation. Soil contamination is, to a great extent, a result of the legacy of inefficient technologies and uncontrolled emissions. Problem areas include some 3,000 former military sites, abandoned industrial facilities and storage sites which may still be releasing pollutants to the environment. One of the major impacts is groundwater contamination and related health problems. Major concerns are the long time needed to regenerate contaminated soil and the considerable investment required for remedial measures.

c) Eastern Europe, the Caucasus and Central Asia: Over the past 50 years, the priority given to increasing the productivity of agriculture, combined with climatic factors, has resulted in soil and water pollution from the overuse of pesticides and fertilisers. Large areas have experienced salinisation as a consequence of unsustainable irrigation schemes and cultivation practices. The most extreme forms of degradation have resulted in the desertification of large areas.

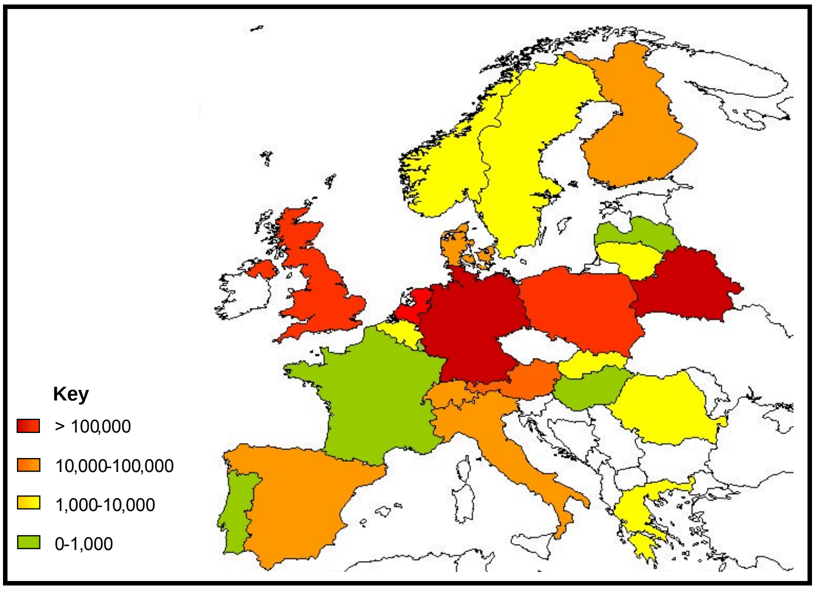


Figure 1. Approximate number of identified contaminated sites across Europe (adapted from [23],[30],[31],[36],[37],[38])

The first step for protecting the community's health from the risks associated to contaminated sites is to identify the sites that present actual hazard to human health and the environment. In this sense, already **about 550,000 sites across the EU have already been identified as definitively or potentially contaminated**. The best estimate is that there are **1.3 million contaminated areas in the EU** [30], although there is still a lack of information about the type and size of these contaminated areas. An estimated overview of the contaminated sites situation in Europe can be observed in Figure 1.

In order to illustrate the scale of the contaminated sites problem in Europe, the available data on the number of potentially and definitively contaminated sites in selected European countries is presented in Annex II.

2.2.1 Characteristic problems

Dangers caused by contaminated sites can be of various kinds, and impairments of water, soil and air and the interrelations between them may have immediate effects on the health of human beings. The extent of the danger or impairment depends considerably on the type and amount of the pollutant on the one hand and the exposition of the protected medium (e.g. groundwater) in any individual case on the other [39]. Threats and dangers to the environment caused by contaminated sites can be seen from the following examples [39]:

- impairment of groundwater quality by contaminated leachate from contaminated sites,
- direct contact (touching, swallowing) with polluted soil (e.g. on a children's playground) on areas formerly used by industry or commerce,
- explosion hazard in case of an accumulation of landfill gas in closed rooms (e.g. cellars),
- contamination of surface waters by pollutants (leachates, run-off) from contaminated sites,
- absorption of pollutants by (useful) plants from the soil,
- vegetation damage due to a displacement of soil air by landfill gas in the root zone of plants,
- damage by settlements and slides of buildings constructed on waste deposits,
- corrosion of underground pipelines and building components due to the impact of contaminated leachates.

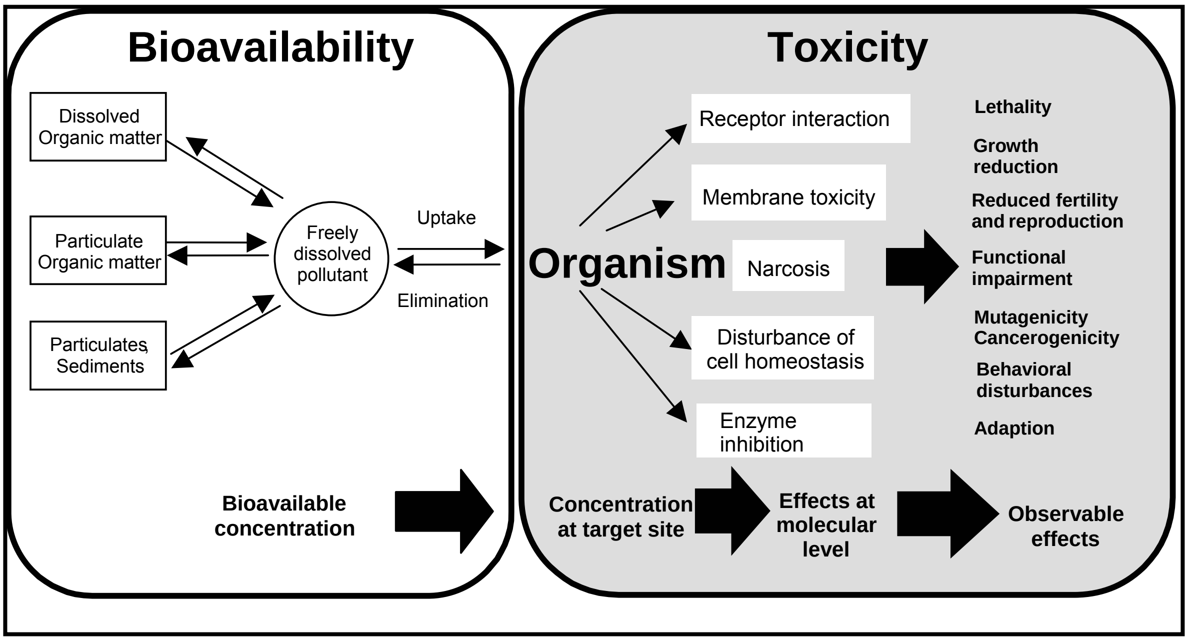


Figure 2. Dependence of the toxicological effects on the bioavailable fraction of pollutants in the environment [40]

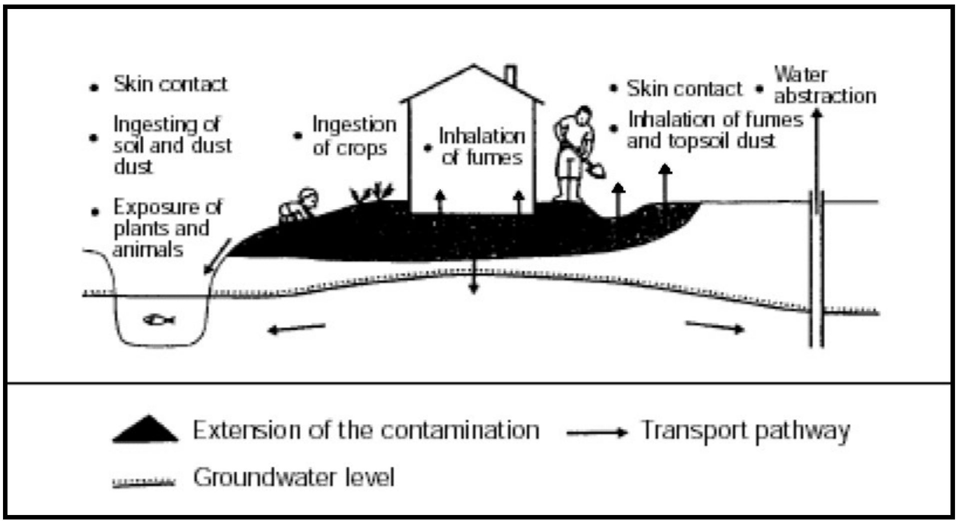
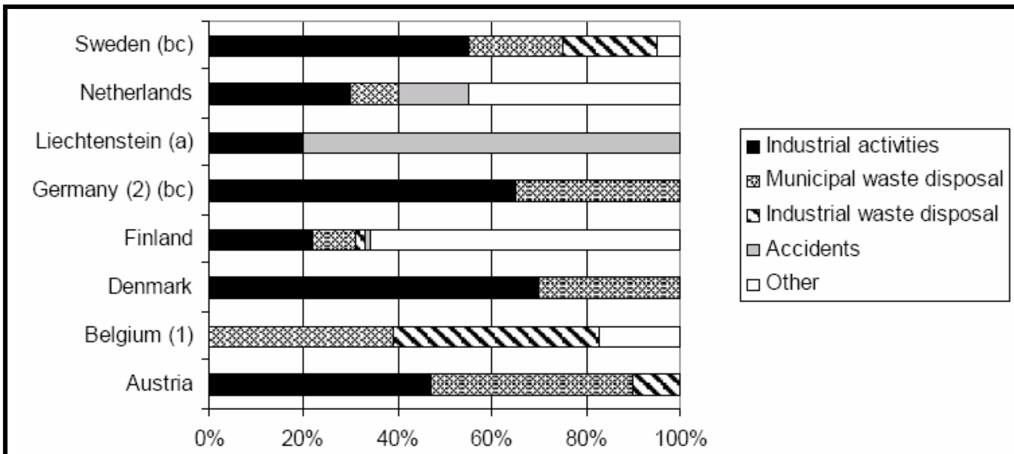


Figure 3. Transport and exposure pathways of pollutants in contaminated sites [41]

2.2.2 Pollution associated with industrial activities and dumping of waste

In most European countries, local soil contamination is mainly due to inadequate municipal waste disposals, to industrial activities no longer in operation, and to past accidents. In some cases, the scale or even the existence of a contamination problem is only established as a result of a new construction project, or following an accident or a natural event (Figure 4). Problems of local contamination are closely connected with the inferior methods of waste disposal used during the past 20 to 30 years - huge amounts of reactive and more or less hazardous waste were deposited without adequate precautions for the protection of the environment - and the increasing use of hazardous substances at industrial and commercial locations. This has led to soil and groundwater contamination due to handling losses, defects, industrial accidents and leaching of hazardous substances at waste disposal sites.



Notes: (1) Belgium: data refer to Flanders
(2) Germany: 'Industrial Activities' also include 'Accidents' and 'Other'; 'Municipal Waste Disposal' also includes 'Industrial Waste Disposal'
(a) minor accidents are not included
(b) the percentage share refers to the total number of identified, suspected sites
(c) data refer exclusively to abandoned sites (not in operation)

Figure 4. Soil polluting activities from localised sources as percentage of total [42]

A wide spectrum of contaminants is expected as a result of the broad range of industrial and commercial activities that can give rise to soil contamination. Major pollutants include organic contaminants such as chlorinated hydrocarbons, mineral oil, heavy metals and, in some parts of Europe, artificial radionuclides. The types of industrial activity (either historical or currently in operation) that pose a risk to soils and groundwater, and the spectrum of various polluting activities, vary between countries. These variations may result in different classification systems and in incomplete information being available in some countries [42].

It must be considered that risks are not just restricted to heavy industrial type operations. Turner et al [43] noted that a broad range of activities have the potential to cause pollution, including light industry and the service sector. Furthermore, they suggest that a prudent property investor may need to look beyond the site-based operations to consider the “indirect risk” associated with tenant operations at other non-owned properties. Annex III gives an indication, not exclusive however, of the broad range of activities that could give rise to contamination of land [44].

Some of the factors that contribute to the overall level of environmental risks associated with a property are also shown in Annex III. Clearly, one of the most significant elements is the nature of site activity, with industrial-type operations likely to be significantly higher risk than service organisations. The age of the site is important for several reasons. For example, environmental control standards such as containment around bulk liquid storage tanks are generally higher for more recent installations. There is also the use of hazardous materials such as asbestos, which are more likely to be found in a building of 1960s or 1970s vintage than a recent building. The production of hazardous waste can also be a significant factor. Industrial-type operators are more likely to produce hazardous solid or liquid wastes; but service operations can also produce environmentally hazardous wastes, for example, restaurants, pharmacists and photographic shops. The proximity of nearby watercourses or vulnerable and sensitive hydrogeology is a significant consideration as these receptors are perhaps those most liable to suffer in an environmental incident [44].

2.2.3 Contaminated sites situation in Austria

In order to obtain a complete understanding of the contaminated sites situation, the Austrian Federal Environmental Agency (FEA) has already worked for several years to identify and investigate the locations where environmentally hazardous substances and materials have historically been discharged and/or deposited [46]. Although the current scope of the Austrian contaminated sites spectrum cannot yet be exactly quantified, several initiatives with this goal are underway and with the intention of producing such information in the upcoming years [46],[47]. The following sections intend to present an overview of the up to date evaluation of the contaminated sites in Austria. As of January 2004 [46]:

- 2,396 sites are registered as potentially contaminated sites,
- 169 have been found to require remediation,

- for 56 sites the risk assessment has shown that no remedial measures are necessary (these sites are to remain under observation),
- 81 sites have been contained or remediated, and
- 51 sites are currently being contained or remediated.

According to the data base of the Federal Office for Environment Protection, stand January 1st 2004, there are a total of 41,410 registered sites, including waste deposits and industrial sites. Table 2 and Figure 5 present the regional distribution of the registered sites [46].

Table 2: Number of registered old deposits and industrial sites in Austria [46]

Federal Province	Waste deposits	Industrial sites	Sum
Burgenland	98	682	780
Carinthia	470	33	503
Lower Austria	912	1,005	1,917
Upper Austria	1,460	9,100	10,560
Salzburg	417	5,601	6,018
Styria	377	4,304	4,681
Tyrol	644	1,449	2,093
Vorarlberg	12	5	17
Vienna	341	14,500	14,841
Total	**4,731**	**36,679**	**41,410**

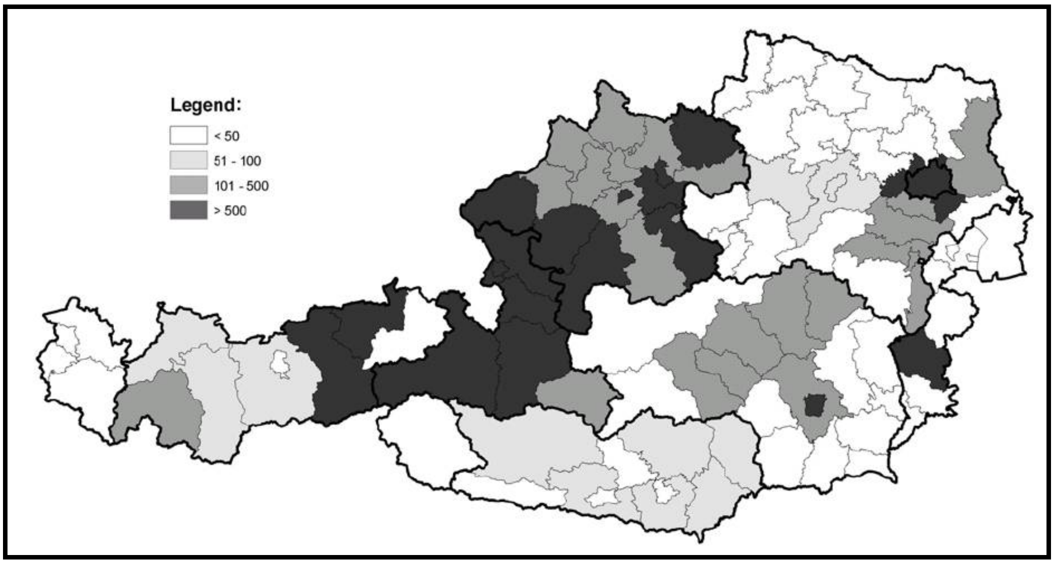


Figure 5. Number of registered sites distributed by regional districts [46].

Table 3 provides an overview on the comparison of the number of currently evaluated waste deposits and industrial sites and the total number of sites estimated by the FEA. The number of waste deposits and industrial sites is not to be equated to the number of the (suspected) contaminated sites. According to the gradual treatment of contaminated sites and in the context of carrying out the Law for the clean-up of contaminated sites, only a small part of the identified sites will be evaluated as suspected sites and as contaminated sites in a further evaluation step [46].

Table 3: Comparison of the number of currently evaluated waste deposits and industrial sites in Austria and the total number of sites estimated by the FEA [46]

Federal Province	Waste deposits			Industrial sites		
	Evaluated	Estimated number	Advance in evaluation (%)	Evaluated	Estimated number	Advance in evaluation (%)
Burgenland	98	300	33	682	2,000	34
Carinthia	470	550	85	33	5,000	1
Lower Austria	912	2,000	45	1,005	14,000	7
Upper Austria	1,460	1,500	97	9,100	9,500	96
Salzburg	417	450	93	5,601	5,700	98
Styria	377	1,200	31	4,304	11,000	39
Tyrol	644	700	92	1,449	6,000	24
Vorarlberg	12	350	3	5	3,000	<1
Vienna	341	400	85	14,500	16,000	91
Sum	4,731	7,450	63	36,679	72,200	51

Figure 6 shows the number of estimated industrial sites, according to their industrial origin, for the most frequent industries [46]. From this figure it can be observed that in most cases, the pollution of the site when existing would have a strong organic load. Polycyclic aromatic hydrocarbons (PAHs) and chlorinated hydrocarbons (CHCs) are among the most common pollutants at contaminated sites all over the world. PAHs appear as primary contaminants in gas works, petroleum, coal coking and mineral oil manufacturing industries' sites, as well as in old wood storage sites, where they have been used as preserving agents [48],[49]. CHCs have been found in sites from solvent and cleaning industries as well as in textile, leather tanning, pulp and paper industries due to their use as bleaching agents. A further source of CHCs presence in lands is their use in agricultural pesticides [50].

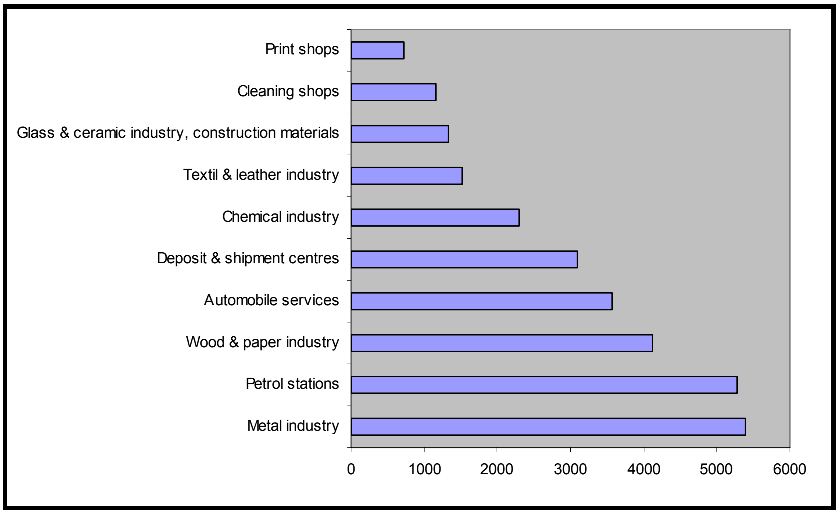


Figure 6. Number of industrial sites in Austria according to their industrial branch [46]

As a matter of fact, in terms of occurrence PAHs and CHCs are the most important pollutants in Austrian contaminated sites. From the 33,549 sites that have been registered as actual brownfields, 163 have already been investigated, evaluated and classified. The data obtained from this evaluation shows that ca. 48 % of the registered contaminated sites presented contamination with either PAHs or CHCs as main pollutants (see Figure 7) [36].

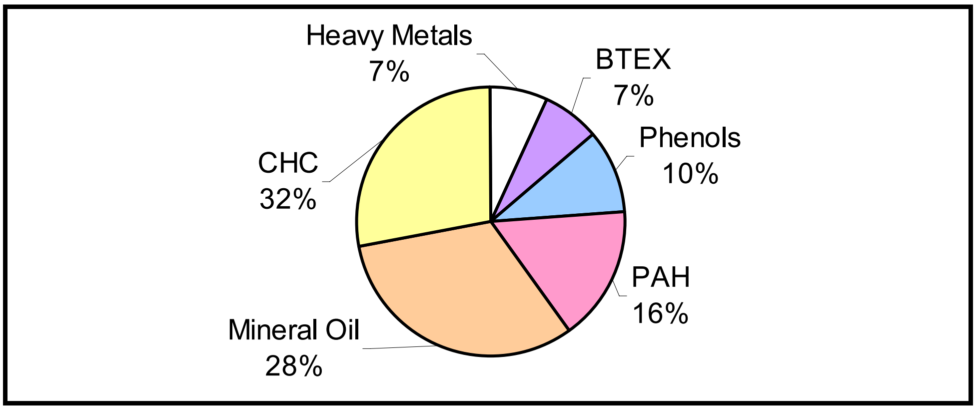


Figure 7. Main pollutants found in Austrian contaminated sites [36].

2.3 Risk assessment of (suspected) contaminated sites

Decision analysis for contaminated sites management is generally carried out through a traditional engineering/economic point of view. However, new advances in human health risk assessment [51],[52], i.e. the probabilistic risk assessment, and the growing awareness of the importance of “soft data” in the decision-making process, require decision analysis methodologies that are capable of accommodating non-technical and politically biased qualitative information [53],[54].

The experience gained through two decades of effort to restore contaminated locations to their native conditions showed that complete cleanup of ground water may not be possible using the existing technologies. Although some sites can be restored to a minimum contaminant level, it is understood that this can be achieved only under favorable hydrogeological conditions, limited extent of contamination, and/or exceptionally active natural attenuation. Moreover, the costs of remediation may reach unexpected heights. In many cases a substantial part of these costs was directed towards contamination present at residual levels that pose little health or environmental hazards [53]. It was then evident that a new management strategy was needed to manage the increasing subsurface contamination in a rational manner. The risk-based management approach was officially born in the early 1990s and advocated by the U.S. Environmental Protection Agency (US EPA) through its guidelines for risk-based cleanup levels [55],[56],[57]. Thus, health risk became an integral component of subsurface contamination control and management [53].

When considering what constitutes an environmental risk in terms of emissions from a site, it can be helpful to view it as consisting of three components - hazard, pathway and receptor. The magnitude of the hazard is related to the nature and quantity of materials and/or process that constitute the risk source. In itself the presence of a hazard might not be significant, as a pathway is required to mean that the hazard can be transported to a target. The nature of the receptor (or target) completes the overall risk profile. A combination of the three factors will determine how significant a risk exists by effectively considering what the probability is of the adverse event and what the consequences would be [44].

- *Hazards:* Typical hazards that might contribute to the environmental risk level at a site might include the storage of hazardous chemicals or fuels, the generation of hazardous waste, the types of construction materials used in the building and ground contamination from current or former site use.
- *Pathways*: In order for hazards to affect potential receptors it is necessary the existence of some form of pathway. Where the hazard is liquid, typical pathways will be either the surface water drainage system, foul water drainage system or, for liquids stored in underground tanks, suitable geology. If the hazard is some form of particulate (e.g. asbestos dust) or excess noise, the pathway would be the atmosphere. Pathways for these potential hazards can be limited by suitable controls (e.g. interceptors for oils on the drainage system).
- *Receptors:* The final major element that affects the potential environmental risk from a site is the receptors. Even if there are a wide range of hazards associated with the site, the absence of sensitive receptors may give the site a lower overall risk. Typical receptors would include local watercourses, groundwater, soil and ecosystems, the atmosphere, neighboring properties, employees or members of the public. The scale associated with the receptor can vary widely. There may be purely local concerns such as those involving neighbors in noise, visual intrusion or other nuisance issues. Acidic atmospheric emissions might cause impacts on a regional scale and greenhouse gases would give rise to global concerns.

Two important factors must be considered when considering environmental risks for land properties, firstly environmental risks are strongly location dependent. The same operation in a different geographical location can represent very different risks. The second consideration is that zero-risk options are not usually available. In relation to the contamination of land, for example, both a no-action scenario (i.e., leave the contamination where it is) and the complete off site removal of contaminants involves risks (which may be quite different in nature and difficult to compare). Removing soil contamination and depositing in a landfill site does not destroy the hazard, however the anticipated overall risk is lower if it is held in a waste facility designed for that purpose [44].

The site dependency of environmental risks is a key factor that differentiates them from health and safety concerns. It may be relatively straightforward to establish a hazard source - pathway - receptor link to assess risks for health and safety (usually depending on operators work behavior). However, off-site information must be gathered to identify the pathway and receptor element of environmental risk. Information that is likely to be required on the pathway and target elements for water will therefore include local ground cover and soil type. The routes and destinations of both foul and surface water drains should also be determined. In tems of off site targets, elernents such as fisheries and public water supplies are important for surface waters. The type and importance of local aquifers is also relevant since they may be used directly as a drinking water source or they may replenish surface water bodies. A first step in this process would involve a review of maps, literature and other information, identifying off site environmental features of the area, including [44]:

- population distribution and local residential patterns;
- flora and fauna with the identification of any important, protected or endangered species and areas of nature conservation values;
- architectural and historic heritage, including archaeological sites, ancient monuments and listed buildings;
- landscape and topographical features; and
- recreational areas, including public rights of way, footpaths and bridleways.

One of the key aspects to consider is the pollution risk to water. The classification of local aquifers and whether there are nearby abstractions as well as information on surface water quality is important.

2.3.1 Preliminary risk evaluation: The EVAPASSOLD assessing model

A new, interesting preliminary risk evaluation assessment model was developed within the framework of the EU-Life project "Evaluation and preliminary assessment of small old deposits (EVAPASSOLD)" [58]. This model is intended to simplify the diagnosis of old, small deposits (i.e. a volume less than 50,000 m³) of the Austrian regions of Lower Austria and Upper Austria. Although formerly developed for small deposits, it represents an interesting strategy to reduce the complexity of first risk estimations. The forthcoming section introduces a summary of the EVAPASSOLD model, as well as its application possibilities.

It has been stated that the Risk (R) model should contain three factors: R_0, f(L/S) and f( ), in the form of eq.(1) [59]:

$$R = R_0 \cdot f(L/S) \cdot f(\ ) \qquad (1)$$

- R_0 deals with the historical background of the old deposits. It considers the kind of residues deposited as well as their deposition age.
- The liquid-to-solid ratio L/S will also comply the information regarding the age and state of the old deposit. Therefore, when multiplied, these two parameters conform what it has been called as "actual material hazard".
- Finally, the f( ) factor will consider all geological parameters regarding the evaluated environmental goods (soil, air, groundwater, surface water).

a) The R_0 factor.

The value of R_0 is changing linearly between the range 1 and 2 for this evaluation. Value 1 means 100 % construction waste and/or excavation waste. Value 2 means 100 % domestic waste. If there is a mix of these wastes, the R_0 factor is set to the following rule:

- Construction waste, excavation materials with 10 % of domestic waste will have an evaluation of R_0= 1.1 (20 % = 1.2; 30 % = 1.3)
- 100 % domestic waste and domestic-like commercial waste: R_0= 2 (containing a maximum of 1 % hazardous waste),

In this evaluation model, when R_0 has a value inferior to 1, the risk factor R will be considered equal to R_0. Moreover, if R_0 has a value superior to 2, the old deposit is out of the range of the EVAPASSOLD model, and thus in both these cases this evaluation procedure is not recommended.

b) The f(L/S) factor.

In order to simplify the application of this model, the following scheme has been developed for the value determination of the function of the liquid-to-solid ratio (Figure 8). According to the EVAPASSOLD model [61],[62] equation (2) shall be considered for the determination of the L/S ratio.

$$\mathbf{F(L/S)} = \begin{cases} 1 & \text{when } L/S < 1 \\ 1.2143 - 0.1429*(L/S) & \text{when } 1 < L/S < 5 \\ 0.5 & \text{when } L/S > 5 \end{cases}$$

Figure 8. Definition of the f(L/S) function

$$L/S = \frac{(I_0 \cdot a_0) + (I_R \cdot a_R)}{m_{DS}} \qquad (2)$$

where:

I_0 *Infiltration into „opened" landfill [mm/a]*
I_R *Infiltration into „closed", recultivated landfill [mm/a]*
a_0 *duration of „opened" deposit [a]*
a_R *duration of „closed", recultivated deposit [a]*
m_{DS} *mass of dry substance in landfill-sector with base area 1 m² [kg_{DS}/m²]*

c) The f( ) factors

These f( ) factors take care of the hydrological aspects of the old deposit. Therefore, a risk evaluation can be performed on basis of groundwater, surface water, air and soil. Their correspondent evaluation parameters are presented in Table 4 to Table 7.

Table 4. Evaluation of the parameter f(G) – risk of contamination effects on groundwater

Parameters for the evaluation of f(G) for groundwater	
1	No utilisation possibilities for groundwater
1.3	Within influence area of water well
1.5	Run-off water, pore groundwater, sufficient only for individual and/or local water supplies.
1.7	Inside a (potential) area of regional and/or national drinking water supply
1.8	All declared sanctuaries and protected areas, groundwater body nationally important
2	All declared sanctuaries and protected areas
> 2	In area of influence of an actual drinking water supply

Table 5. Evaluation of the parameter f(W) – risk of contamination effects on surface water

Parameters for the evaluation of f(W) for surface water	
1	No surface-water within 25 m surrounding and surface-water with possibility of contact to humans no more than after huge thinning of a potential emission and surface water without any special utilisation claim.
1.5	Surface water within directly urban areas or leisure areas (or in nature reserve), larger thinning possible.
2	Surface water within directly urban areas or leisure areas (or in nature reserve), no larger thinning probable resp. utilisation for in-shore filtration recovery or ground water-accumulation

Table 6. Evaluation of the parameter f(A) – risk of contamination effects on air

Parameters for the evaluation of f(A) for air	
1	No utilisation possible and/or contact with humans improbable.
1.2	Utilisation possible (e.g. grassland) and/or contact with humans possible
1.5	Actual agricultural utilisation (e.g. plant production) or location in a natural reserve, eventual fixtures in this area.
1.7	Single urban areas and/or other buildings or facilities for humans as well as leisure areas (parks)
2	Directly urban areas and/or areas with high sensible utilisation (e.g. children‘s playground)

Table 7. Evaluation of the parameter f(S) – risk of contamination effects on soil

Parameters for the evaluation of f(S) for soil	
1	No possible use of surface.
1.2	Agricultural utilisation of surface possible.
1.5	Agricultural utilisation of surface or situation within natural reserve.
1.7	In urban areas without possibility of direct contact to children.
2	Usage of area and/or usage of direct surrounding as leisure area (also children‘s playground).

There are two important considerations before this evaluation model should be used:

- Is the old landfill < 50,000 m^3, with an average deepness of 8 m (i.e., “small deposit”)?
- Are we in the working range ($1 \le R_0 \le 2$) (i.e., household origin deposits) ?

If there are positive answers, it is possible to use the developed ranking system on this site. If one answer is negative, this ranking system cannot be used. A simple scheme regarding the use of this model is depicted in Figure 9.

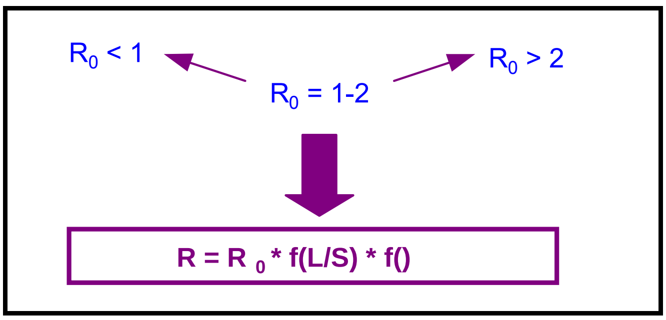


Figure 9. Support model for the first decision in the evaluation of a small old deposit [60].

2.3.2 Baden-Württemberg’s risk assessment model

A danger source can contain materials that endanger the environmental goods (i.e. ground and surface waters, air and soil). These materials can provoke their unfavorable effects only if they actually come into contact with the environmental good. In the danger estimation according to the Baden-Württemberg (B-W) model, apart from the material danger itself, the following balances and processes must be differentiated:

I. Pollutant discharge from the (suspected) contaminated site
II. Pollutant input into the environmental good
III. Transport and effect in the environmental good

I Discharge: With the "discharge" the quantity of the pollutant that leaves the (suspected) contaminated site is described. For the size of the discharge, both the density and the support properties of the material that surrounds the site are decisive.

II Input: If the pollutant has left the danger source, it moves to the respective environmental good. In this case the condition of the underground as well as of the soil and cover material are of importance, since they are the barriers that the pollutant has to penetrate. In these, degradation and sorption processes can take place. In addition, re-mobilization effects may occur. The extent of these effects is decisive for the quantity of the pollutant that enters the environmental good.

III Transport and effect in the environmental good: The pollutants that enter in the environmental good can be subject to further transport and barriers (in particular by degradation and sorption). The extent in which these effects arise depends, just like the extent of possible pollutant effects on the environmental good, on the conditions and characteristics of the environmental good.

The danger estimation must lead to a decision for an appropriate procedure at the danger source, which considers the needs of measures. The following alternatives are possible:

A: Withdraw and file
B: Leave for further samples
C: Specific technical inspection
D: Revision of possible alternatives for danger impairment
E: Investigations

Although the variety of the factors could lead to foster individual case decisions, there is a possibility to perform a uniform procedure. The technical guidelines show that a separate viewpoint of the dangers for the individual environmental goods (ground and surface waters, air and soil) are meaningful, and that material danger, discharge, entry as well as transport and effect at all environmental goods are crucial in the same way. Substantial process steps are given as follows.

The evaluation procedure is an analogy process, which develops on the experiences of known cases. It should serve as a comparative view of the various sites, in order to select from them the most dangerous ones in a relatively simple and direct way. It must provide with the definition of the priorities and a hierarchy of the urgency for taking the measures into practice. For evaluating an individual location, in order to determine its "absolute danger", the procedure is however not suitable. But the procedure can also be used successfully to evaluate the effectiveness of measures for danger reduction. The same is true in the case of cost effectiveness evaluation.

The procedure considers four investigation stages (proof level, or “BN”, see Table 8). They are selected in such a way that, at the end, each investigation stage is a new danger evaluation, both technical and economically meaningful. Thus, a technical and economic optimization of the necessary measures is reached and the proportion of the spent means is guaranteed. The evaluation of suspected contaminated sites takes place in several steps. The individual evaluation steps are taken in sequence (Annex III), but independently accomplished, and in each case the relevant technical criteria are included. Thus a decartelization of the expert knowledge is made possible and the consideration of new results as well as reconstructing the evaluation course is facilitated.

Table 8. Definition of proof levels according to the B-W sites evaluation process

Proof level (BN)	Definition
$E_{0\text{-}1}$	Historical evaluation
$E_{1\text{-}2}$	Indicative/orientative investigations
$E_{2\text{-}3}$	Detailed/Complete investigations
$E_{3\text{-}4}$	Investigations for the proposal of containment and/or remediation measures alternatives

The first step consist in the determination of a material danger (r_0), considering a standardized comparative deposits list ("comparison situation") for the pollutant-loaded waste and soil material. Afterwards, three process steps are taken to determine the actual local conditions regarding discharge (I), input (II), transport and effect (III) (r_I, r_{II} and r_{III} respectively). The influence of local conditions is expressed here in each case in multiplicators, the so-called m-values (m_I, m_{II}, m_{III}). The gradual adjustment of the risk to local conditions takes place as follows:

$$r_I = m_I \cdot r_0$$
$$r_{II} = m_{II} \cdot r_I \qquad (3)$$
$$r_{III} = m_{III} \cdot r_{II}$$

The determined **actual risk** (r_{III}) is weighted according to the meaning of the environmental good or property in a fourth process step ($r_{IV} = m_{IV} \cdot r_{III}$). As a rule this risk is then determinant for the further procedure (relevant risk R). In order to estimate the relevant risk to the action need, it is necessary to characterize the proof level (see Table 8). By combination of BN with the relevant risk in a process matrix (Figure 10), the action need can be derived in a simple manner.

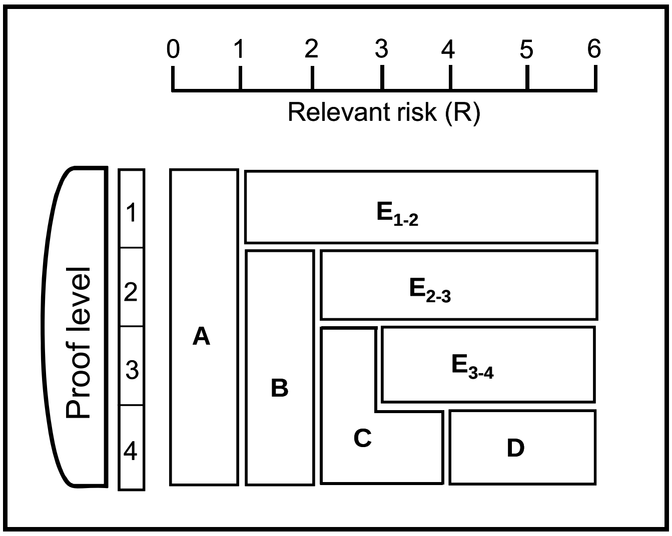


Figure 10. Action need determination according to the B-W evaluation process.

Bases and results of the evaluation as well as verbal and written statements of experts must be laid down in register logs. Thus the met decisions remain comprehensible (e.g. for possible legal arguments, claims for damages, etc.). Besides, an electronic evaluation form is available for the documentation of the evaluation results. In addition the data for r, m, R and BN are clearly shown. Supplementing data concerning the quality of the available information (determined = "F", suspected = "V", unknown = "U") is also given. As "action need" the action need derived from the action matrix (A, B, C, D, E1-2, E2-3, E3-4) is registered. The concrete technical measures for the realization of the action need (e.g. the sinking of a groundwater measuring point, or chemico-physical investigations in the groundwater) must be then specified on the basis of technical criteria. For each environmental good, a separate evaluation form must be completed. If at a danger source different groups of materials occur spatially separately and/or different site and underground conditions are present, it can be necessary to perform separate evaluation forms for each one of them.

2.4 Contaminated sites management: State-of-the-art description

The management of contaminated sites brings a reduction of the community health risks. Moreover, decontaminating these sites creates opportunities for redevelopment activities that will bring jobs, housing and open space opportunities to communities that badly need them [23],[26],[63]. However, the selection of the best site contaminant containment and/or remediation technology is not an easy task, especially considering the current proliferation of technologies for managing both polluted sites and groundwater [9],[27],[28]. After an initial euphoria to clean all contaminated locations, authorities have realized that a “one-size-fits-all” remediation strategy is not feasible, as there are several different parameters to take into account in the selection process of the most appropriate technology. Moreover, in the last years, site redevelopment has been incorporated as a new process variable for the decision on the site management technology to be used, as it entails a technological/economical aspect to the management strategy.

The decision for the best site securing and/or remediation technology is therefore not a routine task either, especially considering the current proliferation of technologies for managing both polluted sites and groundwater, as it may be observed in Figure 11 and Figure 12 [64]. Physical, chemical and biological processes have been the most useful techniques depending on the physicochemical parameters of the soil and the kind and concentration of pollutants.

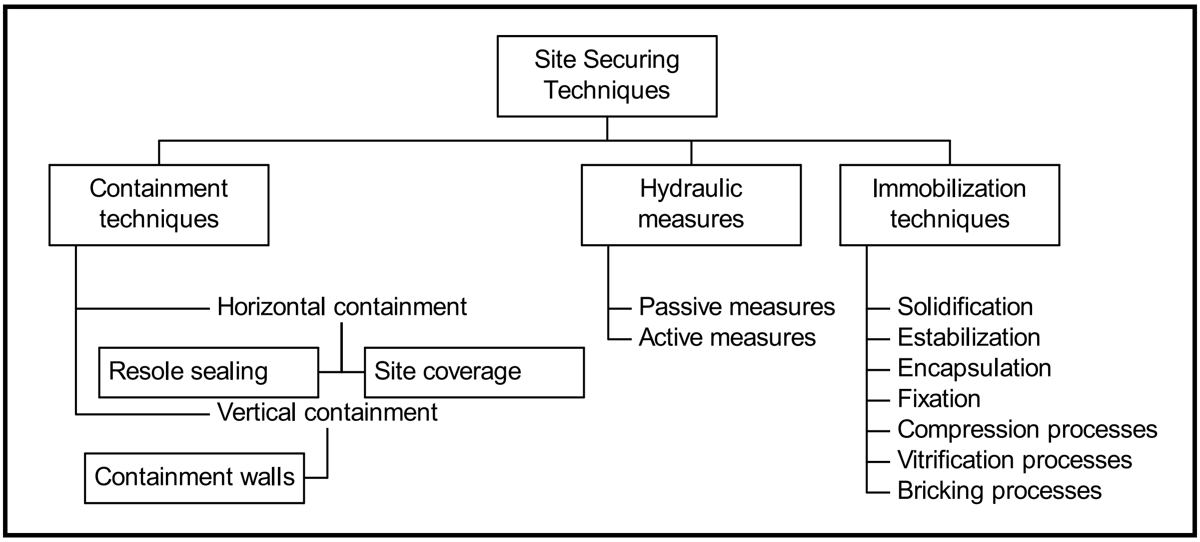


Figure 11. Summary of securing techniques [64],[65],[66]

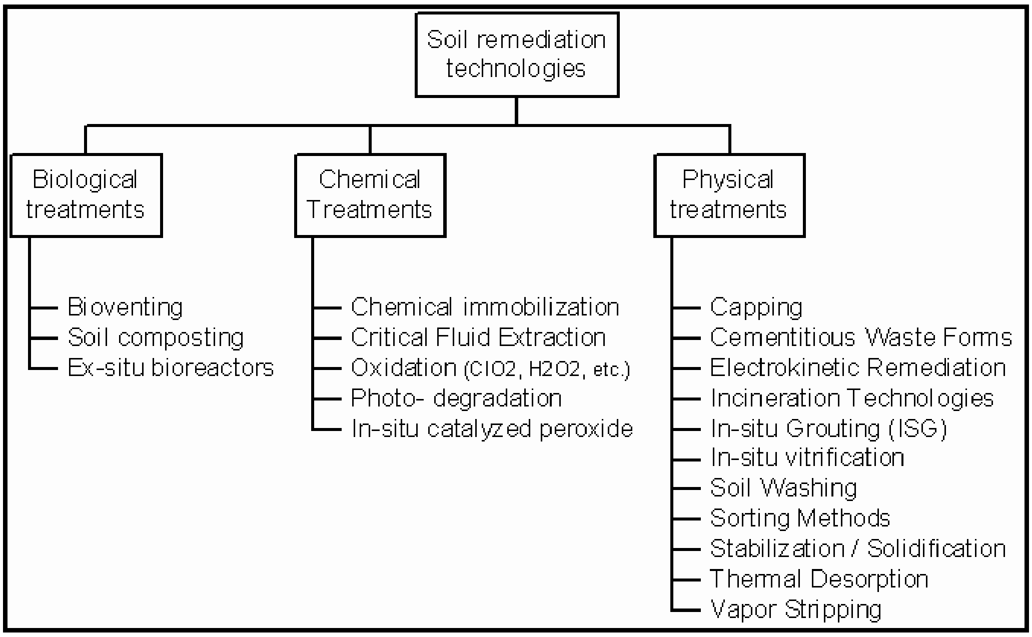


Figure 12. Summary of soil remediation technologies [9], [28],[64].

In general it is possible to define two different types of remediation processes: in-situ and ex-situ. In-situ processes are carried out in the same place where the pollutant is present, while ex-situ processes are carried out in on-site or off-site plants or facilities. On-site refers to the place directly at the contaminated site, while off-site indicates that the place of a remediation facilitiy is located far from the contaminated site.

Relative to ex situ technologies, in situ technologies may be a more cost-effective and less intrusive means of remediating contaminated soils, sediments and groundwater. Excavating contaminated material, as well as operating and maintaining facilities for ex situ treatments often result in higher costs for treatment on the surface. Unlike ex situ remediation, in situ technologies can be used at a site with little disruption to ongoing operations. In situ treatments require neither heavy equipment for excavation, nor large above-ground surface areas for facilities for treatment technology equipment.

Because in situ remediation occurs with contaminated materials in place, it minimizes exposing humans and the environment to contaminants. In contrast, transferring subsurface contaminated materials to the surface increases the risk of exposure for the same receptors. For the reasons given above, as well as others such as inability to excavate contaminated material, or political or public opposition to ex situ approaches, in situ treatment may often be the preferred approach to remediation. However, a fundamental requirement of in situ methods is the accesability of the site for the treatment to be applied.

On the other hand, to use an ex situ approach, one must remove contaminated soil from its original location and treat it above ground. Although the excavation process may be expensive, seeking an ex situ solution can have several advantages. Any conventional in situ remediation scheme such as bioremediation or soil vapor extraction can be applied to the excavated soil, and since the soil is usually handled in a closed system, process operational control is greatly simplified. Aggressive remediation schemes such as surfactant or acid leaching can be applied without posing a threat to the environment. Often this cannot be done in situ for fear that mobilized contaminants will escape containment or contaminate previously uncontaminated soil. Furthermore, the performance of treatment process can be more easily monitored and unsuccessful proceses may be abandoned with little environmental risk since the pile remains encapsulated until satisfactory results are attained.

In addition, gradual, long term remediation techniques can be used to provide low cost, low risk remediation that would not be feasible in situ. This is similar to using in situ “natural attenuation”, but allows for superior mass transport control while the process proceeds. Also, since wastes are removed from their original locations, much of the original site can be quickly recovered. This can be a compelling advantage for redeveloping the affected areas where a small portion of the site can be dedicated to gradual remediation while the remainder of the site is redeveloped, or where one small site can host the remediation for several similar locations [67].

2.4.1 Contaminated sites investigation and evaluation

The basis of every decision is information. Only if there is correct and sufficient information, we are able to define a goal and determine a way to achieve it. The local geological/hydrogeological conditions determine the practicability of a project, its complexity and its costs. Already at the stage of the definition of the goal or the problem there has to exist a certain knowledge of the local geology, the area´s history of use and the requirements of land-use planning [68]. Therefore, regardless whether the problem is in the subject of water supply development, problems of soil contamination or construction projects, the first step is always to conduct a thorough investigation and presentation of the available data. The planning of every project happens on the basis of existent information and the project goals as defined in consent with the client. For a closer investigation of the geological and hydrogeological setting or the actual situation of contaminations, the range of actions has to be planned individually. Official reglementations are to be regarded [68].

Contaminant site characterization is one of the most intensively studied subjects in hydrogeology during the past 20 years. Numerous technical methods exist to obtain soil, gas and water samples from the subsurface through wells and cores (Figure 13). In addition, a lage variety of *in-situ*, *on-site* and *off-site* chemical and microbiological analysis techniques exist with well estabished sampling and Quality Assurance (QA) [69] protocols. Generally, one can distinguish between invasive and non-invasive investigations, the latter based on geophysical methods. However, characterisation of the subsurface environment is still a complex problem, as it may be observed in Figure 13 [70].

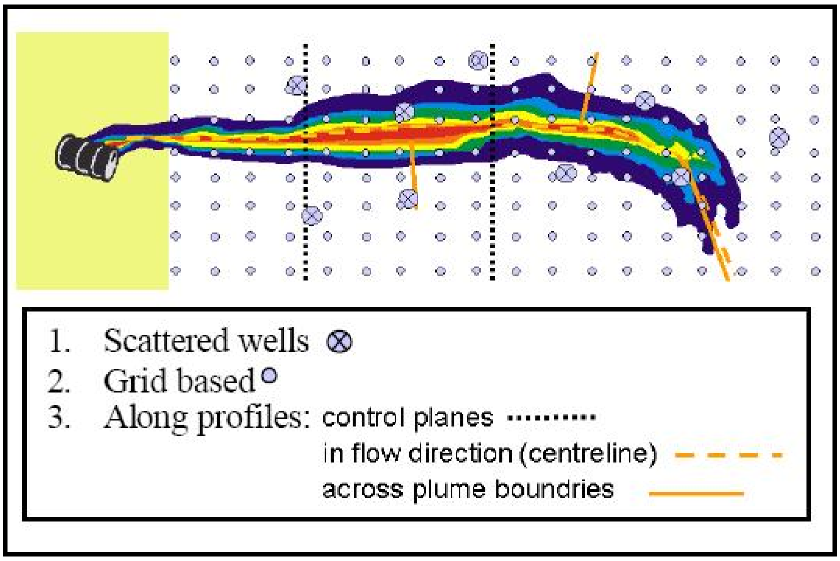


Figure 13. Different approaches to plume characterization [70].

The assessment of the actual or potential degradation of groundwater resources at contaminated sites involves a combination of investigations that are both time-consuming and costly. It is the aim of such investigations to determine the amount of contaminants and where they can be found and, ideally, what the temporal development is likely to be. Due to the pressure of time, money or both, such information often cannot be obtained in the most cost-effective manner. Further, in the absence of scientific criteria for cleanup with clean-up goals, inappropriate solutions and extensive chemical monitoring may result. In order to avoid these problems, a 3-step approach to site remediation is generally recommended (e.g., [71]). A preliminary investigation involving the collection and viewing of available information precedes the physical investigation of the site and the last step is a comprehensive site assessment and a feasibility study of site restoration measures [72].

The quality of the hydrogeological information that must be gathered for the assessment of any site is, to a large degree, dependent on the siting of boreholes. There are several approaches that have been developed to increase the efficiency of hydrogeological investigations (e.g., [73],[74]). A number of field tested alternatives are commercially availale in Europe, which can offer some solutions to these difficulties. The most important alternatives to drilling are technologies where a probe is pushed into the ground using percusión or continuous pressure. Moreover, a number of techniques have been developed to work in a tandem with these technologies to facilitate soil and groundwater sampling, and also *in-situ* real-time sensing [75]:

Solids sampling: Techniques for removing soil cores include pushing a steel tube into the subsurface at a specified depth, or in a continuous way by pushing a cone with a hollow point into the soil and catching the "soil saugage" in a liner. A variety of products and configurations are commercially available.

Groundwater sampling: Extraction of groundwater samples always involve the introduction of a filter in the soil at the required depth. Penetration techniques are based on pushing a closed filter system into the ground which can be opened at the desired depth. A number of products are available. For some products, after sampling the probe can be withdrawn, washed and used at another location. These are not permanent groundwater monitoring wells that allow continuous monitoring. Others can introduce a permanent monitoring point. These products introduce smaller filter depths than the one or two metre filtres posible for traditional boreholes. This can limit sample volumes, but has the advantage of offering a fairly fine degree of resolution over depth.

2.4.2 Containment technologies

Containment techniques prevent the spread of contamination outside of a defined boundary. In-situ containment implies that the contaminants are left in place and the containment is installed around the contaminated zone. In general, contaminants are not destroyed or removed with this technique although hydraulic containment does remove contaminants dissolved in groundwater. In-situ containment is the preferred solution for contaminated sites for which in-situ treatment or excavation are either impossible or prohibitively expensive. Containment is usually considered the option of last resort since no real cleanup is achieved and the site usually has severe use restrictions placed on it. Containment options are mainly designed to contain liquid contaminants or groundwater from flowing beyond the site boundaries. However it can also be used for soil contamination where the potential for leaching of contaminants exists or where other pathways of exposure such as airborne volatile releases exist. Containment can be achieved either by installing physical barriers such as grout curtains, slurry walls, sheet piles or surface caps or by installing hydraulic control measures such as pumping wells, trenches or drains.

Pumping is the most commonly used technique because it is fairly easy to install and tends to be more effective than physical barriers. The pumping of groundwater however means that the pumped water must be either treated or discharged. Thus hydraulic containment systems need long-term operational planning and funding.

The present work addresses the most common containment technologies (see Figure 14), i.e. pumping and cutoff trenches as hydraulic methods, and slurry walls, grout curtains, sheet piles and surface cups as physical methods. A technological description is given, as well as a comparison among their application according to the site's condition.

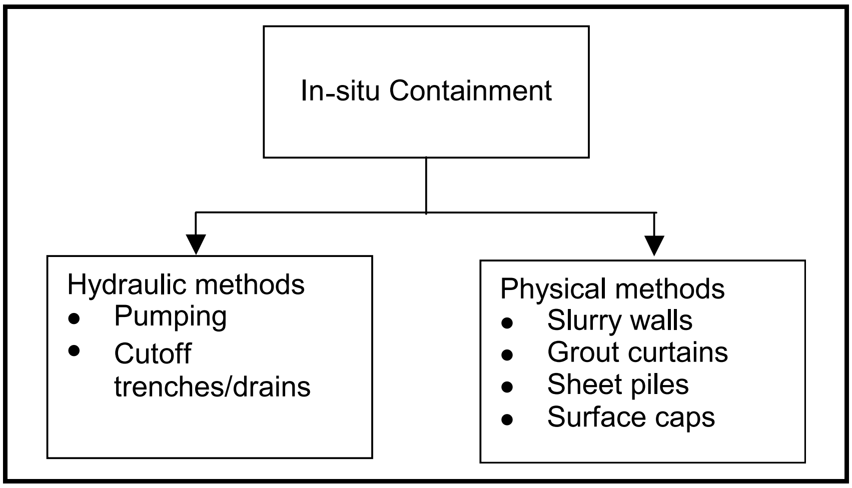


Figure 14. Sub-options of in-situ containment addressed in this work [80]

2.4.2.1 Hydraulic Containment techniques

a) Pumping

For sites with a plume of contaminated groundwater, hydraulic containment through pumping of groundwater is always an option. Pumping of groundwater contains or reduces the contaminant plume by stopping or reversing the natural flow of groundwater. The water table around each pumping well is lowered to the point where the water table in the immediate vicinity of the pumping well is lower than the water table at any other point in the contaminant plume. The groundwater then flows towards the pumping well and is extracted. Groundwater extracted through pumping must either be treated or directly reinjected to the aquifer, depending on the level of contamination. If the groundwater is treated at the surface then the entire operation is called "pump and treat". Reinjection of groundwater without treatment is occasionally chosen as an option either because the groundwater does not require treatment or because the flushing action of the re-injected water is intended to clean the soil or bedrock. Figure 15 illustrates a specific example of hydraulic containment [80].

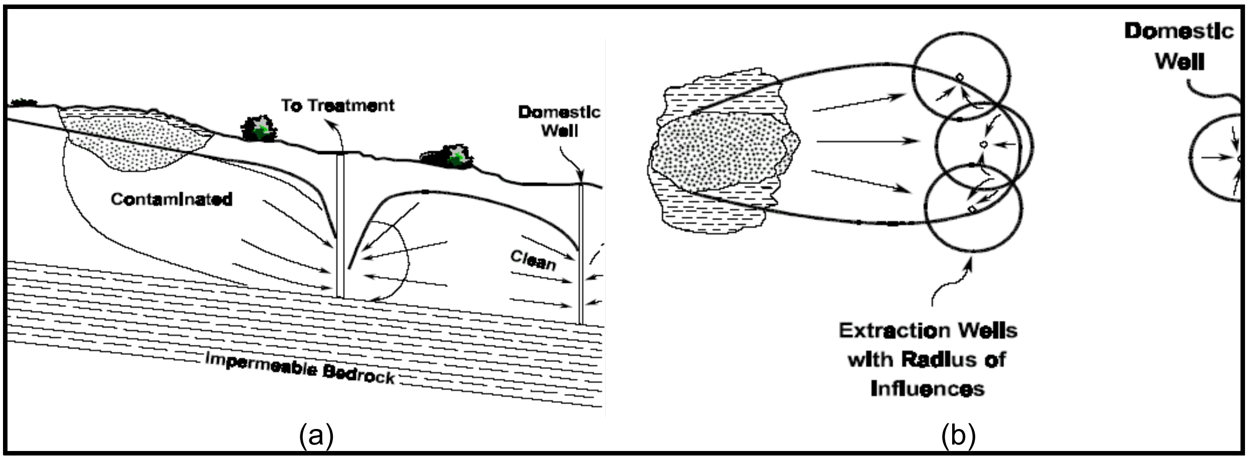


Figure 15. Example of hydraulic containment. (a) cross-sectional view, (b) plan view [80].

When designing for hydraulic control, the following factors should be considered:

- size of plume or contaminated property;
- groundwater flowrate and direction of flow;
- proximity of site to existing groundwater extraction wells;
- hydrogeologic conditions
- pumping rate needed to control plume;
- positioning of extraction wells to achieve containment;
- expected height and profile of water table at steady state pumping;
- expected concentration of contaminants in pumped water (modelled over time);
- effects of re-injection of groundwater if this option is being considered; and
- environmental effects of pumping (e.g. impact on water levels in nearby surface water).

The potential disadvantages of pumping systems to achieve hydraulic control are:

- hydraulic control may be required for a very long time (hundreds of years); some jurisdictions require the site owner to set up a fund to pay for the operating costs;
- not all aquifers are amenable to pumping;
- not all contamination systems can be contained with pumping; in some cases the plume has divided into several plumes and moved under neighboring properties and cannot be retrieved through pumping;
- pumping conditions can change over time, and the system must be re-designed;
- not all contaminants can be treated or re-injected safely; and
- there is a high degree of uncertainty related to the effectiveness of pumping before installation because of the variability of subsurface conditions (i.e., a planned pumping system may not work as planned).

b) Cut-off Trenches and Drains

Hydraulic control of some sites can be achieved using trenches or subsurface drains to intercept groundwater flowing into or out of a site. This option is usually considered only for shallow groundwater conditions. Water entering the trench or drains flows either by gravity or by pumping to a treatment site or discharge area. Trenches and very shallow drains have the added benefit of collecting surface run-off if this is desired at the site. Trenches are often used for emergency cleanups where contamination is flowing rapidly and needs to be prevented from reaching an environmental receptor. A cut-off trench or drain system placed upgradient of a contaminated site is designed to prevent clean groundwater from entering the site (and becoming contaminated). Also the cut-off of the flow into the site slows or ceases the flow of water out of the site since the driving force for the groundwater (the head) has been removed. Water collected in this cut-off system is usually clean and is often discharged to surface water.

A cut-off trench or drain placed downgradient of a contaminated site will collect contaminated water flowing out of the site. As with pumping systems, this water must either be treated or recycled back to the site to flush more contaminants. Some form of treatment must be available because not all water can be recycled back to the site. Since shallow water tables are heavily influenced by rainfall there will be times when the site cannot accept more water without flooding the ditches or drains.

Factors which must be considered when designing cut-off trenches or drains are:

- size of plume or contaminated property;
- groundwater flowrate and direction of flow; seasonal variations in flow;
- hydrogeologic conditions;
- elevation of site above or below nearby discharge points;
- positioning of trenches and drains to achieve containment;
- need for pumps and storage basins;
- expected height and profile of water table at steady state;
- expected concentration of contaminants in collected water (modeled over time);
- effects of re-injection of groundwater if this option is being considered; and
- environmental effects of drainage (e.g. impact on water levels in nearby surface water).

The disadvantages of cut-off trenches and drains are:

- If used as a long-term solution, they have all the same disadvantages as pumping;
- cannot control water deeper than about 10 metres below surface;
- cannot control vertical movement of groundwater;
- trenches open to air may give off volatile emissions; and
- open trenches need special safety measures.

2.4.2.2 Physical Containment techniques

Whereas hydraulic containment systems contain contamination by causing or allowing groundwater to flow, physical containment systems attempt to prevent groundwater from flowing out of the site. Vertical Engineered Barriers (VEBs) are subsurface barriers made of an impermeable material designed to contain or divert groundwater (Figure 16). VEBs can be used to contain contaminated groundwater, divert uncontaminated groundwater from a contaminated area, or divert contaminated groundwater from a drinking water intake or other protected resource [80],[81]. Different techniques are used for the construction of a physical containment system, as presented in the following sections. A comparison of these technologies is found in Annex IV.

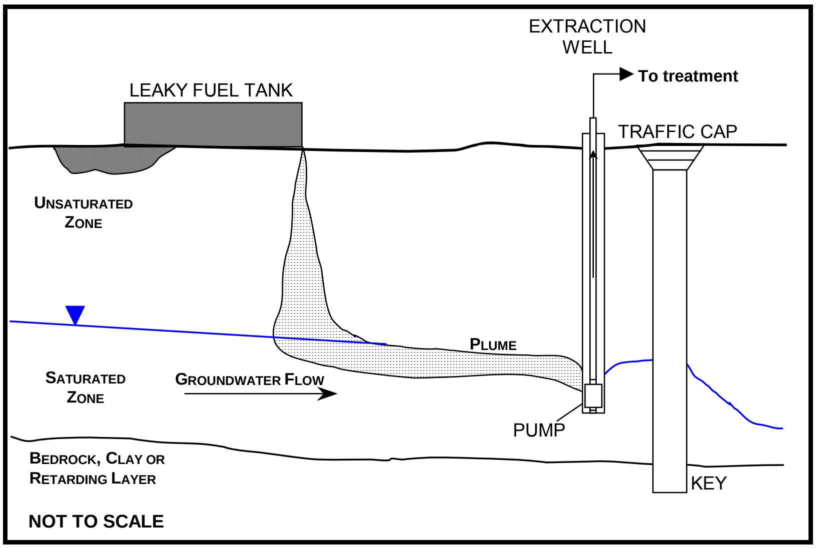


Figure 16. Model of a vertical engineered barrier [82].

a) Slurry Walls

Slurry walls are made by digging a trench around all, or part of, a contaminated site and filling the trench with a slurry which, when cured, forms an impermeable barrier to groundwater flow (Figure 17). The slurry is usually made with bentonite and water, and in some cases is solidified by adding soil and more bentonite or adding cementing agents so that it cures and hardens over time. The trenches must be dug either into an impermeable layer below the contaminated zone or to a point below the contamination at which the groundwater outside the walls will not mix with the water inside the walls. Sites using slurry walls can be capped with an impermeable material to prevent infiltration of rainwater.

Figure 17. Overview of a slurry wall installation in an Austrian remediation project.

b) Grout Curtains

Grout curtains are similar to slurry walls except that a slurry (the grout) is injected into the soil through drilled boreholes instead of filling a trench with slurry. Injection is achieved with a variety of different equipment and methods but all systems use high pressure to force the grout slurry into the pore spaces of the soil. Usually a standard drill rig is used to drill the holes where the grout is to be injected. Injection is performed at numerous points around the site so that eventually an impermeable barrier or "curtain" is formed. Many different types of grout are available including bentonite, cement, silicates, ligneous materials and organic chemicals. Grout can be injected to a considerable depth and can be selectively injected to only a certain depth if this is desirable.

c) Sheet Pile Walls

An impermeable wall can be created by driving sheet piles into the ground around all or part of a site. Sheet piles are sections of steel plate, usually corrugated for strength, which can be driven into the ground using a pile driver. As seen in Figure 18, the sheets interlock at the edges so a continuous subsurface wall can be guaranteed. The small gap at the interlocking points can be filled with grout or will seal itself with fine particles over time. The sheet piles can be ordered from a steel supplier in any length however there are restrictions on the height of pile driving equipment normally available. Walls have been driven to 20 metres deep, although with special equipment this depth could be increased.

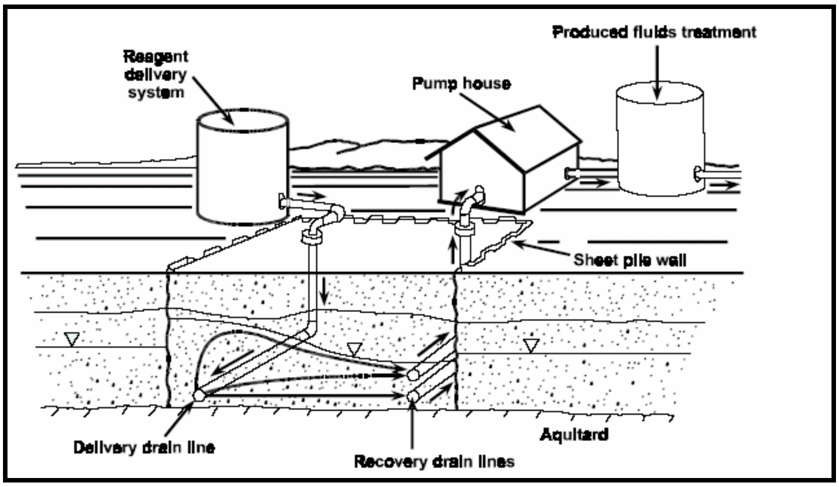


Figure 18. Example of sheet pile walls used in recovery of ground water [80]

d) Thin cut-off wall (vibrating beam wall)

This containment system receives its name from the thickness of the cut-off wall which is about 10 to 20 centimeters. The wall is constructed by driving a steel beam into the ground then extracting the beam while injecting a waterproof grout into the cavity thus formed. Then the beam is repositioned to overlap the previously filled cavity and so forth. The beam can be hammered or vibrated (with or without jetting) to the required depth (see Figure 19).

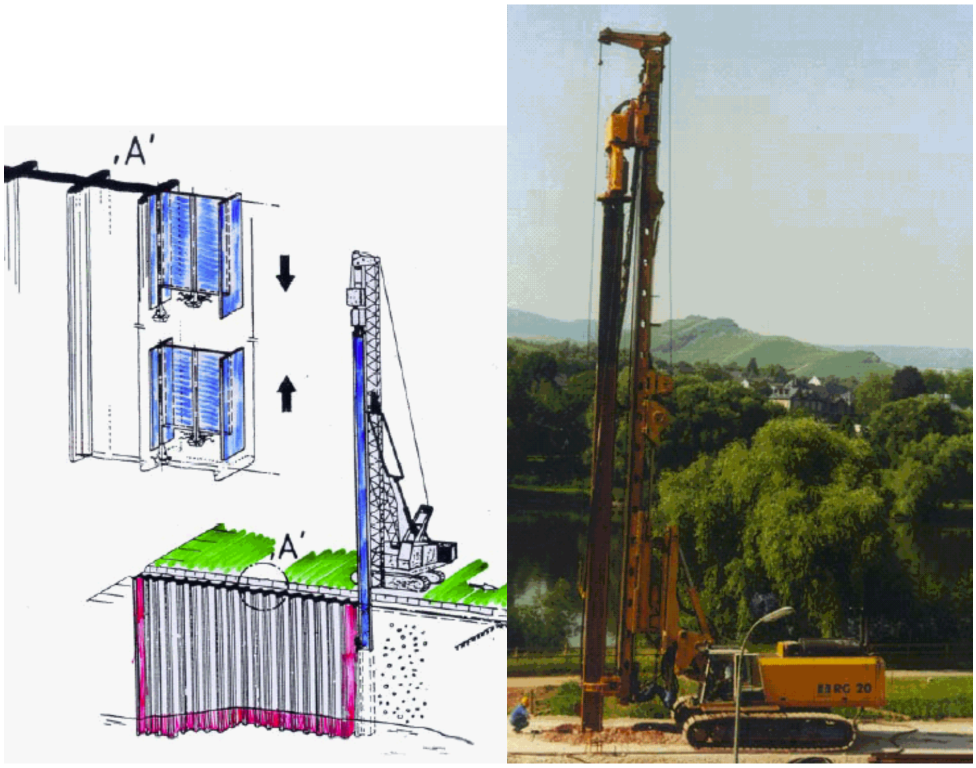


Figure 19. Overview of the vibrating beam wall process [85].

Since, with this method, the ground is compacted rather than excavated, the wall depth is limited to 20-25 m even using the most powerful equipment; in addition, this method does not apply to all types of ground [83]. Although this type of barrier is sometimes called a slurry wall, it is more closely related to a grout curtain since the slurry is injected through a pipe in a manner similar to grouting. The vibrating beam technique is most efficient in loose, unconsolidated deposits, such as sand and gravel [84].

e) Surface Caps

Capping is one of the most common techniques for managing sites, although it is usually used in combination with other techniques such as containment or in-situ treatment. A cap is a layer or several layers of material placed over the contaminated site. Total cap thickness is usually at least 0.5 metres and often is 1 metre or greater. The cap may be designed to be impermeable, semi-permeable, permeable to specific substances only or permeable. The permeability of the cap is dictated by the other control or treatment mechanisms at the site, the amount of rainfall and overland flow expected, the expected exfiltration of water and vapours and the planned end-use of the site.

Impermeable caps are designed to keep all rainwater and surface water from infiltrating into the contaminated zone and also to prevent contaminants from seeping out of the site. These caps are usually made of several layers of material including one or more impermeable layers. The impermeable material is usually either compacted clay or a plastic sheet (specialty plastics like HDPE, i.e. high density polyethylene, made for this purpose). Other layers are geofabric, sand and topsoil. Geofabrics are used to prevent erosion or to hold another cap layer in place. Some sites need to have gas vents inserted through the cap to allow the release of vapours.

Permeable or semi-permeable caps are usually used in conjunction with an in-situ treatment system or a hydraulic containment system. These caps are made to allow a certain amount of water to infiltrate into the site or to allow off-gases to leave the site. These caps are constructed similar to impermeable caps except the impermeable layer is omitted. In some cases a layer of reactive or soluble material such as limestone, fertilizer, fly ash or specially formulated agents are added. Infiltration of rainwater carries the disolved reactive material down into the ground where in-situ remediation is occurring. Caps are relatively inexpensive and remove the threat of contaminant exposure through surface mechanisms. Most caps need to be maintained as erosion and shifting of materials under the site can damage the cap. Many caps have been employed so successfully over the last 100 years that people are not aware that a contaminated site exists beneath the surface of the ground (note however that this lack of awareness has caused problems related to exposure to contamination and land use - capped sites should always be zoned for “no development” and the potential hazards clearly posted).

f) Vienna chamber system

The landfill at Rautenweg, originally a gravel pit, is located in the northeast of the city, on the edge of the Vienna Basin. With a size of 55 hectares, it has a landfilling capacity of 13.7 million m³, as defined in the operations permit that was granted under the provisions of the relevant water protection regulations. The Rautenweg site is Vienna's only landfill for landfill class III waste, which includes municipal solid waste, grit chamber material, residues from waste-to-energy plants, mineral wastes, soil and sand sludge, etc [86].

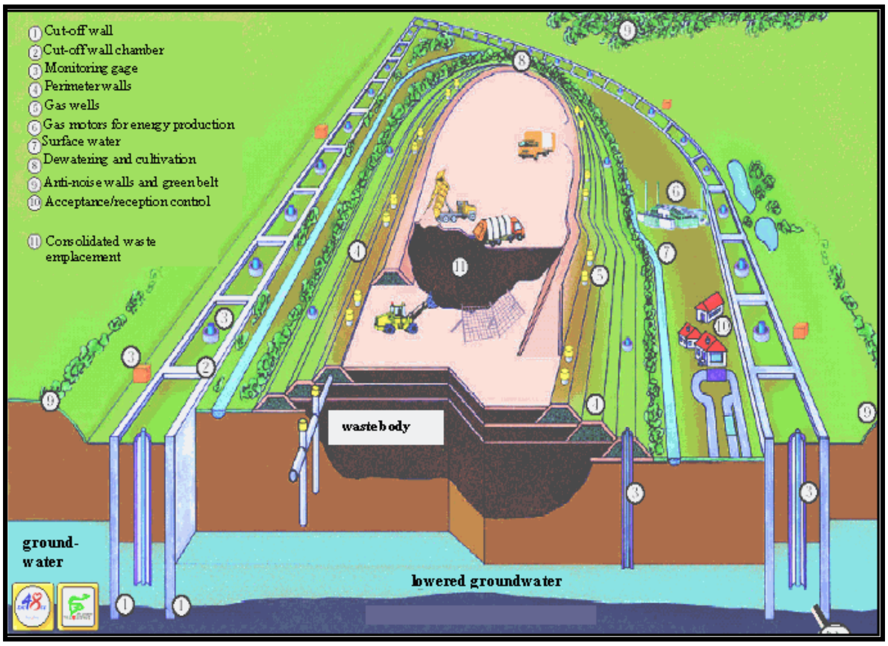


Figure 20. Overview of the Vienna chamber system [86].

Because the original landfill was constructed without leachate collection, an elaborated system, known as the Vienna Chamber System, has been developed to protect the groundwater (see schematic illustration in Figure 20). Parallel retention and groundwater retention walls (up to 43 m into the ground) divide the landfill into 49 different ‘chambers’ [87],[88]. Within the containment system, the water level is kept lower than outside, and in the cells, a water level between the inside and outside levels is maintained, resulting in a hydraulic head that prevents any release of contaminated water from the enclosed landfill area. Any changes in groundwater flows (caused by a bank up of inflows or a depression of outflows) are balanced out by a supply well in the west and an absorption well in the east, which are connected by a circular conduit for this purpose. An online measuring system, to which the responsible municipal authority is directly linked, serves for continuous function monitoring of the Vienna Chamber System within the context of regular operations [86].

2.4.2.3 Considerations when planning to use a Containment System

Containment techniques are very situation-specific and a great deal of site characterization and modelling work is usually necessary before selecting a technique. In some cases the modelling may show that containment will not work. Table 9 (see page 39) highlights the situations where containment, in-situ treatment, pump and treat and excavation may or may not be applicable.

Table 9. Considerations in the use of physical containment, hydraulic containment, in-situ treatment and excavation [80]

Situation	Physical containment	Hydraulic containment/ Pump and Treat	In-situ treatment	Excavate soil or material
Contaminated soil, vadose zone only	Yes	No	Yes	Yes
LNAPL [a] contaminated soil, saturated zone	Yes	Yes, but likely will not remove contaminants from soil completely	Yes	Often difficult
DNAPL [b] contaminated soil, saturated zone	Probably not	Yes, but only to contain plume, will not remove signi-ficant amounts of DNAPL	Probably not	Often difficult
Drums or tanks of wastes or products	Yes, but not preferred	Yes, but not preferred	No	Yes, preferred
Soluble contaminants in shallow aquifer	Yes	Yes	Yes	No
Soluble contaminants in deep aquifer	Difficult	Yes	Yes but often difficult	No
Free product (liquid)	Not recommended	Yes	Difficult	Yes in some cases
Radioactives	Yes	Yes	No	Very expensive and dangerous

[a] LNAPL: Light Non-Aqueous Phase Liquid, [b] DNAPL: Dense Non-Aqueous Phase Liquid

2.4.3 Soil remediation technologies

2.4.3.1 Bioremediation

Bioremediation uses microorganisms to degrade organic contaminants in soil, sludge, and solids either excavated or in situ. The microorganisms break down contaminants by using them as a food source or co-metabolizing them with a food source. Aerobic processes require an oxygen source, and the end products typically are carbon dioxide and water (although also metabolites can be found as intermediates [48]). Anaerobic processes are conducted in the absence of oxygen, and the end products can include methane, carbon dioxide, hydrogen gas, sulfide, and elemental sulfur.

a) Ex-situ bioremediation

Ex situ bioremediation includes slurry-phase bioremediation, in which the soils are mixed in water to form a slurry to keep solids suspended and microorganisms in contact with the soil contaminants, and solid-phase bioremediation, in which the soils are placed in a cell or building and tilled with added water and nutrients. Land farming, biopiles, and composting are examples of ex situ, solid-phase bioremediation (Figure 21).

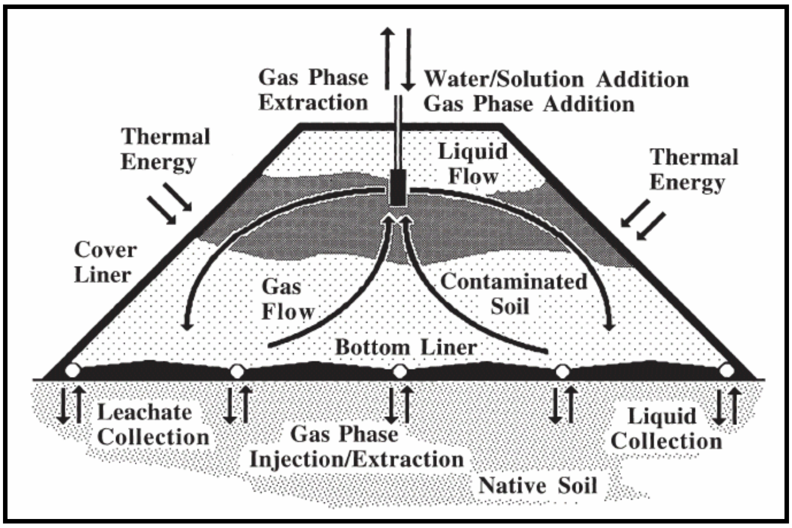


Figure 21. Conceptual geometry of an ex situ soil pile [67].

An interesting feature of soil pile treatment is that it is well-conditioned for supporting sequential remediation processes. Remediation problems are often complex. Soils are rarely contaminated by a single pollutant. Often one finds a mixture of organic and inorganic contaminants that cannot be remediated with a single process. The most commonly applied processes (soil vapor extraction, groundwater pump-and-treat and bioremediation) all can leave behind a significant portion of many problems.

The sequential treatment approach has great appeal since one can employ preliminary treatment steps to solve problems that would otherwise degrade the efficiency of subsequent processes. For example, one might begin by applying vapor extraction to remove low molecular weight organics, and sequence to another process (e.g. anaerobic bioremediation) when the efficiency of the process and volatility of the remaining contaminants declines. One might also begin treatment with a soil leaching process to remove heavy metals that inhibit bioremediation, and then sequence to uninhibited bioremediation. Sequencing also means that an unsuccessful remediation process does not necessarily mean failed remediation. Another process can be applied without any risk to the environment since the soil pile would remain encapsulated until remediation is successful. Also, because the soil pile is encapsulated, “innovative” technologies can be applied with better monitoring and control. It is also easier to add “accelerating” features to standard remediation processes. One can, for example use solar radiation to accelerate temperature-sensitive processes or use soil moisture control (added for bioremediation, removed for vapor extraction) to improve performance.

b) In-situ bioremediation and soil aeration

In situ bioremediation techniques stimulate and create a favorable environment for microorganisms to grow and use contaminants as a food and energy source. Generally, this means providing some combination of oxygen, nutrients, and moisture, and controlling the temperature and pH. Sometimes, microorganisms that have been adapted for degradation of specific contaminants are applied to enhance the process. Bioventing is a common form of in situ bioremediation. Bioventing uses extraction wells to circulate air through the ground, sometimes pumping air into the ground.

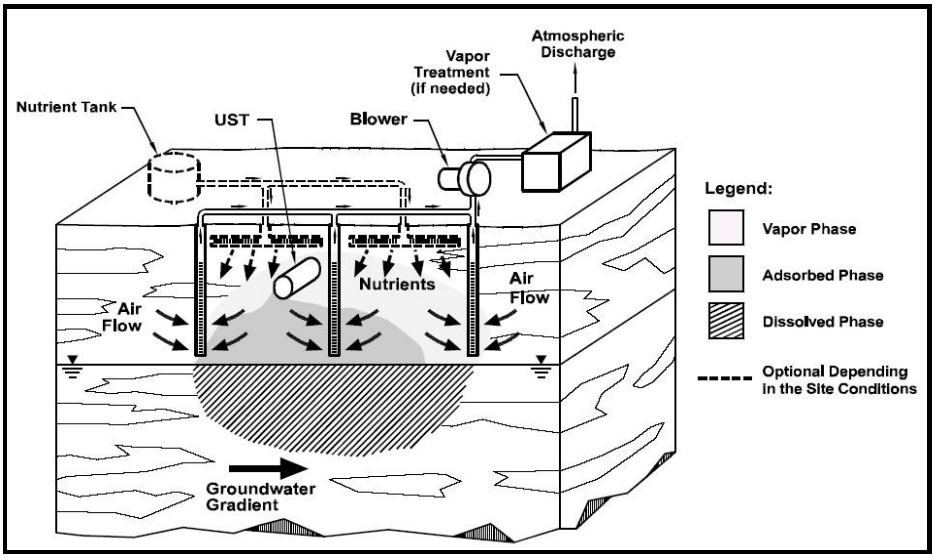


Figure 22. Typical bioventing system using vapor extraction [89].

As mentioned above, injecting oxygen into an active landfill or contaminated site can induce on-site aerobe decomposition of organic contaminants. The BIOPUSTER® process provides the necessary optimised aeration of the waste body. During the BIOPUSTER® treatment air or oxygen enriched air is injected with pressure impulses of 2 to 6 bar. The resulting flow behaviour ensures that cracks and pores as well as closely packed areas of the waste body are equally supplied with oxygen. Thus methane producing anaerobe processes are stopped and microbiological aerobe decomposition can take place instead. The products of these aerobe decomposition processes are mainly carbon dioxide and water. To encourage and speed the aerobe decomposition oxygen enriched air is used, whereby the concentration of oxygen can be adjusted to circumstances on-site and usually varies between 30 and 35%.

Paralleling the aeration, the produced decomposition gases are sucked off and subsequently cleaned by a filter device (Figure 23). The extracted gas amount usually exceeds the amount of injected air/oxygen mixture by approximately 30%, thus ensuring low pressure conditions in the waste body. This way, unchecked gas emissions on the landfill surface can be avoided. The adequate duration of this aerobe pre-treatment is crucial for the success of the conditioning of any waste body. As our tests clearly showed, a pre-treatment period of only a few days would mean that, after some hours, anaerobe processes will take over again, which in turn lead to the renewed production of harmful landfill gas by anaerobe conditions. From the many successful applications of the BIOPUSTER® a necessary treatment period of at least 3 to 4 weeks can be estimated, thus ensuring the aerobe stabilisation of the waste to be completed, and the material being fit to be excavated, sorted, transported to other facilities and subjected to further treatment. The utilisation of the BIOPUSTER® technique prior to excavation of a landfill is an essential precondition for professional remediation of old waste dump sites [90].

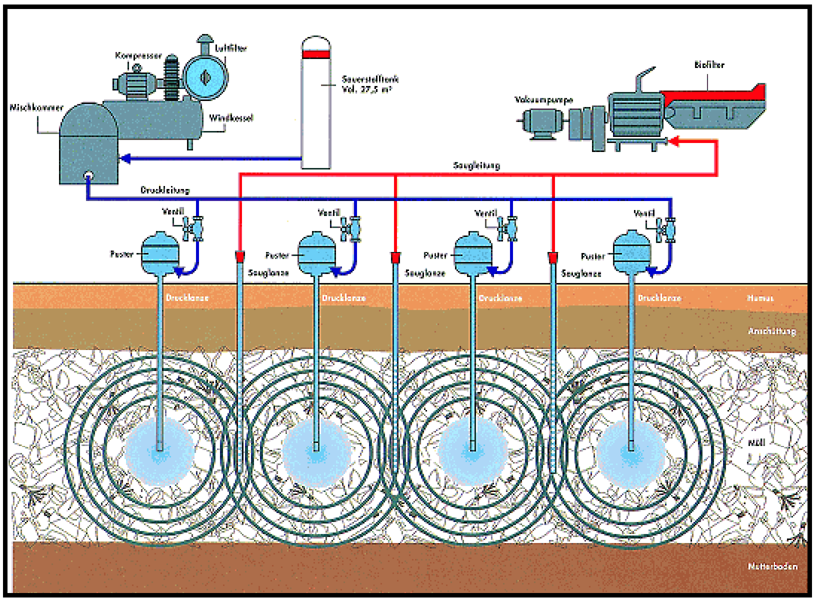


Figure 23. Schematic overview of the Biopuster process

2.4.3.2 Thermal Treatment

a) Incineration

Both on-site and off-site incineration use high temperatures, 870 to 1,200°C, to volatilize and combust (in the presence of oxygen) halogenated and other refractory organics in hazardous wastes. Often, auxiliary fuels are employed to initiate and sustain combustion. The destruction and removal efficiency for properly operated incinerators exceeds the 99.99 percent requirement for hazardous waste and can be operated to meet the 99.9999 percent requirement for polychlorinated biphenyls (PCBs) and dioxins. Off-gases and combustion residuals generally require treatment. On-site incineration typically uses a transportable unit; for off-site incineration, waste is transported to a central facility. Incineration is used to remediate soils contaminated with explosives and hazardous wastes, particularly chlorinated hydrocarbons, PCBs, and dioxins. Factors that may limit the applicability and effectiveness of the process include [91]:

- Only hazardous waste incinerators are permitted to burn PCBs and dioxins.
- There are specific feed size and materials handling requirements that can impact applicability or cost at specific sites.
- Heavy metals can produce a bottom ash that requires stabilization.
- Volatile heavy metals, including lead, cadmium, mercury, and arsenic, leave the combustion unit with the flue gases and require the installation of gas cleaning systems for removal.
- Metals can react with other elements in the feed stream, such as chlorine or sulfur, forming more volatile and toxic compounds than the original species. Such compounds are likely to be short-lived reaction intermediates that can be destroyed in a caustic quench.
- Sodium and potassium form low melting point ashes that can attack the brick lining and form a sticky particulate that fouls gas ducts.

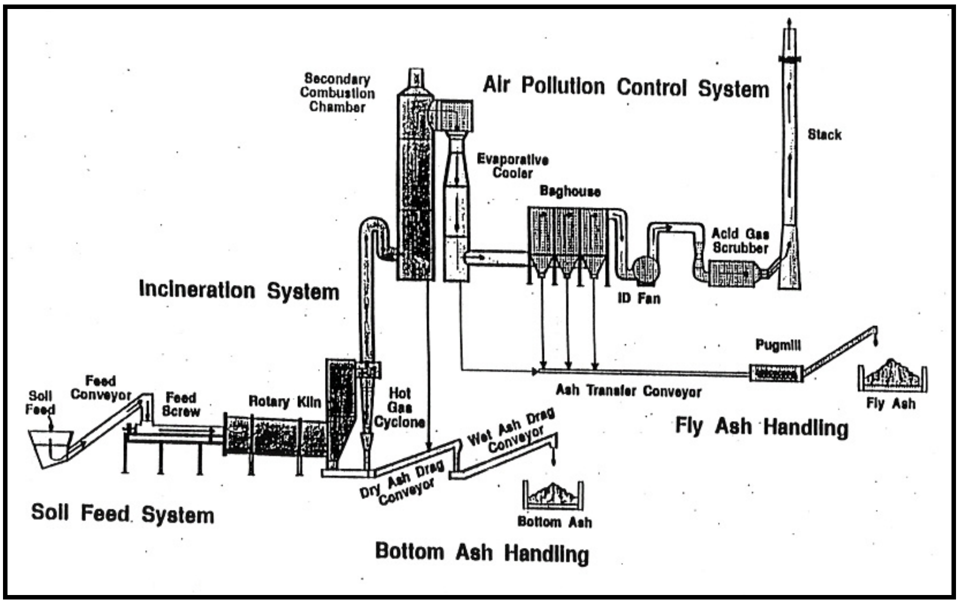


Figure 24. Schematic overview of a soil incineration plant [92].

b) Thermal Desorption

For Thermal Desorption, wastes are heated so that organic contaminants and water volatilize. Typically, a carrier gas or vacuum system transports the volatilized water and organics to a gas treatment system. Based on the operating temperature of the desorber, thermal desorption processes can be categorized into two groups: high temperature thermal desorption (HTTD) (320 to 560°C) and low temperature thermal desorption (LTTD) (90 to 320°C), see Figure 25 and Figure 26, respectively. HTTD has proven it can produce a final contaminant concentration level below 5 mg/kg for petroleum hydrocarbons and BTEX. LTTD is a full-scale technology that has been proven successful for remediating petroleum hydrocarbon contamination in all types of soil. Contaminant destruction efficiencies in the afterburners of these units are greater than 95%. The same equipment could probably meet stricter requirements with minor modifications, if necessary. Decontaminated soil retains its physical properties. Unless being heated to the higher end of the LTTD temperature range, organic components in the soil are not damaged, which enables treated soil to retain the ability to support future biological activity. Two common thermal desorption designs are the rotary dryer and the thermal screw. Rotary dryers are horizontal cylinders that can be indirect- or direct-fired. The dryer is normally inclined and rotated. For the thermal screw units, screw conveyors or hollow augers are used to transport the medium through an enclosed trough. Hot oil or steam circulates through the auger to indirectly heat the medium. All thermal desorption systems require treatment of the off-gas to remove particulates and contaminants. Particulates are removed by conventional particulate removal equipment, such as wet scrubbers or fabric filters. Contaminants are removed through condensation followed by carbon adsorption, or they are destroyed in a secondary combustion chamber or a catalytic oxidizer. Most of these units are transportable. Thermal desorption is normally an ex situ treatment process.

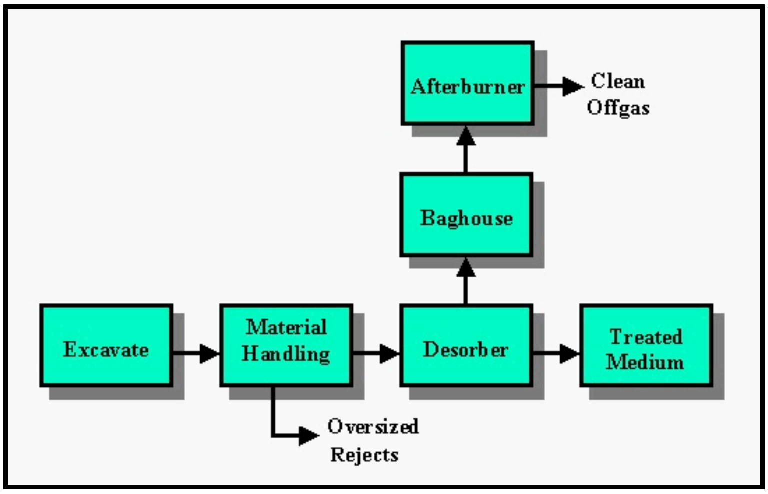


Figure 25. Typical High Temperature Thermal Desorption Process [91].

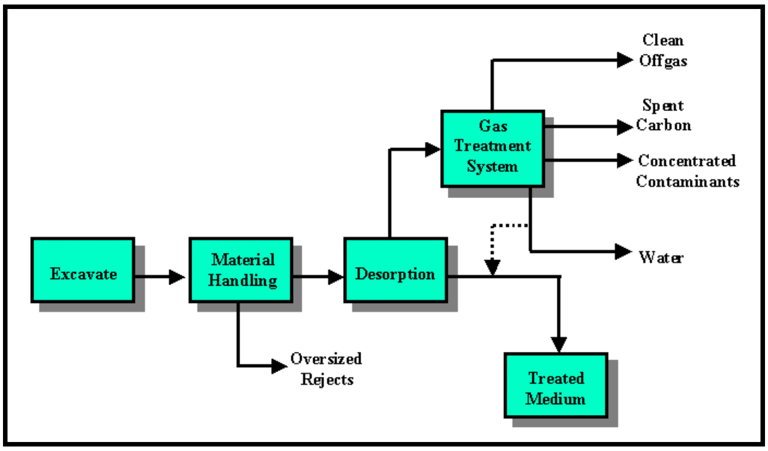


Figure 26. Typical Low Temperature Thermal Desorption Process [92].

In-situ thermal desorption methods [93] are of interest as an approach to soil remediation for volatiles and semi-volatiles through ground heating using, for example, radiofrequency heating, thermal blanket heating, and steam injection heating. Application of these techniques requires knowledge of desorption kinetics and transport of contaminants in soil as a function of temperature [94],[95].

2.4.3.3 Excavation, physical separation and off-site treatment and disposal

Contaminated solids/sludges are excavated, dredged, or pumped from surface or sub-surface areas, typically staged for loading (treated if required), and loaded into transport vehicles for shipment to an approved receiving facilitsy (e.g., a licensed landfill). Soils can be excavated with backhoes (Figure 27A), front loaders, continuous excavators, scrapers, or other equipment. Submerged sediments are often removed using a dredge. Physical Separation processes (called “triage”) use different size sieves and screens to concentrate contaminants into smaller volumes. Most organic and inorganic contaminants tend to bind, either chemically or physically, to the fine fraction of the soil. Fine clay and silt particles are separated from the coarse sand and gravel soil particles to concentrate the contaminants into a smaller volume of soil. The smaller volume then can be treated further or disposed. Material may be dewatered using staging operations. Settling and decanting, filter or belt pressing, or centrifuging, if needed, can perform dewatering.

(a) (b)

Figure 27. Phases of soil excavation: (a) Soil excavation with backhoe, and (b) Loading of the sieve facility for soil fractioning [96].

Pretreatment (stabilization, fixation, or encapsulation) of material may be required to bind free water and prevent leachate development from the excavated wastes once disposed of off site. Pretreatment processes are usually done during staging. Liquids generated during dewatering may also require treatment prior to shipment or discharge. Loading may be direct (e.g., from the bucket excavator) but is more typically done with front-end loaders after stockpiling, classifying, and pretreating solids and sludges. Waste materials are typically disposed of in permitted treatment, storage and disposal facilities [80],[82] like landfills, municipal solid waste incinerators or hazardous waste incinerators. Cleaned and/or low contaminated soil material can be reused as filling material and for recultivation.

A state-of-the-art alternative is the **encapsulated excavation under roof** (Figure 31). In this case, a closed hall is implemented at the excavation area (and alternatively for the excavated material manipulation activities, i.e. triage, as well as for the storage of the sorted material fractions). Through the construction and implementation of these facilities it is intended to prevent the emissions from the restoration activities (i.e., dust, off-gases, noise) as far as possible. A further advantage is the isolation of the working areas from climatic conditions (e.g. rain water) and the hindering of further infiltration of surface water into the site's body.

Figure 28. Under roof excavation procedures.

Figure 29. Under roof triage operation.

Figure 30. Drum-sieve for triage of excavated material under roof. Overview of the air extraction during the triage process.

In these projects, a substantial attention must be given to the collection and treatment of the exhaust air from the operational areas (which should include all sites under roof in case of separated facilities for the handling and storage of the excavated material). Moreover, the on site security conditions for the workers must be fostered by maintaining a permanent ventilation in the halls and the use of machinery with cabines for the drivers which are sealed and provided with forced ventilation devices (see Figure 29 and Figure 30) [97],[98].

2.4.3.4 Soil Vapor Extraction

Soil Vapor Extraction (SVE) is used to remediate unsaturated (vadose) zone soil. A vacuum is applied to the soil to induce the controlled flow of air and remove volatile and some semivolatile organic contaminants from the soil. SVE usually is performed in situ; however, in some cases, it can be used as an ex situ technology [81].

SVE, soil aeration and bioventing, all involving the drawing or injecting of air through the vadose soil region above the water table, are variations of one technology proven in recent years to be effective and comparatively inexpensive in removing hydrocarbon contaminants. The remediation takes place in two ways: (i) by desorption and vaporization of the volatile organic constituents (VOCs) of the chemical spill, carrying them in the soil gas phase to a collection point at the surface where they can be concentrated and disposed of; (ii) by increasing the subsurface oxygen content thereby accelerating biodegradation of the hydrocarbons by microorganisms already subsisting in the soil. The two functions are not necessarily mutually exclusive although operating conditions may promote one over the other [99]. Some biodegradation may occur where vapor extraction is desired and vice versa. Stimulated biological activity has been estimated to account for 15 to 80% of total hydrocarbon removal at different sites under various conditions [100],[101],[104]. Soil vapor extraction and bioventing generally utilize the same equipment while their system configuration and operation may be designed for their different functions.

Typically, an SVE system operates as follows: A vacuum blower mounted at the extraction well draws air, originating from outlying intake wells and, where possible, from the surface open to the atmosphere, through the contaminated vadose soil. The air desorbs and vaporizes the VOCs and carries them through the extraction well to a knock-out drum where grit and water vapor are removed. The VOC-laden air stream is then sent to a gas treatment facility where the VOCs may be flared, adsorbed on carbon or catalytically oxidized. The SVE wells are typically constructed of PVC pipe and are valved together in such a way that some wells may be used either for intake or extraction. The wells are frequently configured based upon what is perceived to be the optimal arrangement, given knowledge of the soil characteristics and the contaminant distribution. The soil surface is sometimes covered by either a High Density Polyethylene (HDPE) liner or bentonite clay for a temporary site or by asphalt for a site which will later be built on. This layer prevents the vertical draw-down of air from the surface, which might cause a short-circuiting problem around the extraction well, and promotes horizontal gas flow. A number of demonstration projects and large-scale recovery operations over the last years have shown the effectiveness of SVE technology in remediating vadose soil [104],[105].

2.4.3.5 Soil Washing

The aim of soil washing is to produce a clean sand fraction from the soil that can be reused, for example, as a building material. Next to the sand, a fine residue is produced as a sludge in which the contamination is concentrated and which has to be de-watered and disposed by landfilling or thermal treatment (Figure 31 and Figure 32).

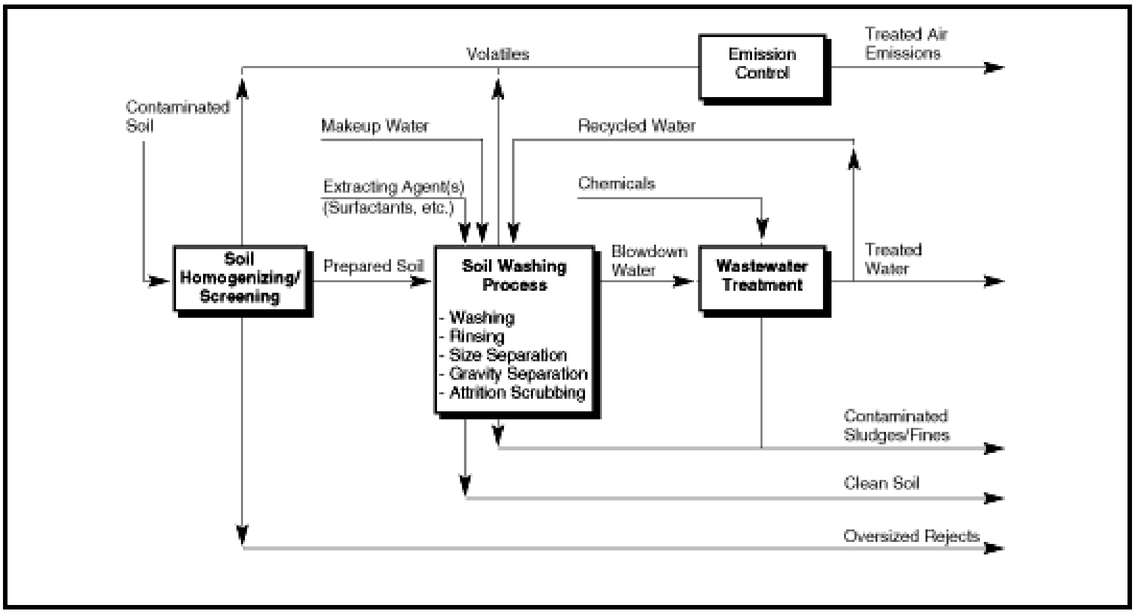


Figure 31. Typical scheme of a soil washing process [106]

Figure 32. Ex-situ soil remediation with on-site soil washing facility [96].

Sometimes a rubble fraction is produced as a separate product or residue. Depending on the quality, this rubble fraction may be applied as a building material or landfilled as well. Soil washing is a viable option for contaminated sandy materials if a large part of the material can be recovered as reusable sand at reasonable cost [102],[103].

Contaminants sorbed onto fine soil particles are separated from bulk soil in a water-based system on the basis of particle size. The wash water may be augmented with a basic leaching agent, surfactant, a chelating agent or by adjustment of pH to help remove organics and heavy metals. Soils and wash water are mixed ex-situ in a tank or other treatment unit. The wash water and various soil fractions are usually separated using gravity settling.

2.4.3.6 Considerations when planning soil remediation projects

As for containment techniques, all remediation technologies can be characterized by their applicability, as well as the advantages and disadvantages of their selection. Table 10 (page 50) summarizes these characteristics for the most utilized technologies in remedial projects.

2.4.4 Active and passive groundwater remediation technologies

Ex situ treatment of groundwater by “pump and treat” consists of extracting contaminated groundwater, treating the extracted water, and discharging or reinjecting treated water. In comparison to treating contamination in situ, extracting contaminated materials for treatment on the surface may pose a greater risk of exposing humans and the environment to the contaminants. In the case of extracted groundwater, this increased risk could result from possible exposure to contaminated off-gases generated by some ex situ treatment technologies, and by spills.

Table 10. Applicability of different remediation processes [108],[109]

Process	Application	Advantages	Disadvantages
Micro-biological process	For organic compounds in permeable soils (Mineral oil – Sand/Gravel k_f=10^{-3} m/s). In general, not for CHC (except low concentrations) and inorganic compounds. Not suitable in constructed areas. PAH, Phenol, BTX-Aromatics, HCH and Mineral Oil are substances with complicated degradation	Cost effective. Low environmental ballast. Pollutants degradation. Low energy demands. (Generally) good acceptance from communities.	Performance strongly dependant on life conditions of organisms and underground permeability. No control for in-situ applications. Hygienic problems possible due to unexpected pollution dispersion. Possible mobilization of substances through changes in the biological and geo-chemical conditions. High oxygen demand. Long degradation times.
Immobilization	Containment, separation and degradation of pollutants as well as fixation in soil for the prevention of emissions into atmosphere and biosphere. For phenols, some heavy metals (Pb, Cr, Zn, Hg), radioactive waste, metal-ceramic compounds for which neither bio-logical nor soil washing process are suitable.	Diminishment of mobility and permeability of the under-ground. Extensively proved processes. Mechanically stable soil as end product.	Limited temporal success. Same reagent can immobilize one group of contaminants whereas at the same time mobilizing others. In-situ operation can provoke further deterioration of soil and groundwater. Pollutants are not removed.
Extraction (washing process)	Mainly suitable for coarse soil. Only for soluble substances of organic and inorganic nature. Selective for heavy metals. For permeable soil with mixed pollutants. Not suitable for loamy or clay soils. Not suitable for soils with fine fraction > ¼ of the total soil mass. Suitable for Cyanide, Mineral Oil, HCH, BTX, Phenols, PAH, Dioxines, PCB, Herbicides, Pesticides.	Separation of pollutants. Largely demonstrated for organic and inorganic pollutants. Possible reutilization of the treated soil. Relative short process times. No transport costs by using mobile facilities.	Performance and complexity strongly dependant on soil type, situation and concentration of pollutants. Necessary removal and disposal of pollutants from the extraction solution. Possible remains of extraction solution in soil. Energy intensive.
Thermal treatment	For all organic compounds in high concentrations. For all soil types. Necessary combination of treatment for off-gas and wastewater. Consider after no alternative is available. Only suitable for some inorganic pollutants (Heavy metals: Hg, Cd), Cyanide. Suitable for Mineral Oil, HC, HCH, PAH, PCDD, PCDF, BTX, Non ferrous metals, PCB, Pesticides, Dioxines, TNT.	High efficiency, available technologies, destruction of pollutants, relative short operational times, removal of all organic pollutants.	Changes of soil structure and composition, depending on temperature treatment. Cost intensive. Possible formation of dioxins and furans at high temperatures. Dead soils as product. Generally low community acceptance.
Soil air extraction	Light volatiles organic pollutants from the unsaturated zone. Soil types: from sand to low cohesive soils. Not suitable for loam or clay soils. Normally combined with thermal, biologic or soil washing processes. Suitable for BTX, HCH, PCB.	Protection of the treated soil.	Only for selected pollutants. Performance strongly dependent on soil type, soil temperature and moisture. Necessary gas treatment and disposal.

An important advantage of ex situ remediation technologies centres around the ease of monitoring their effectiveness. For example, sampling is easy, and the source of samples is readily identified. In the case of in situ treatments, sampling soil and groundwater is more difficult, making monitoring somewhat less effective.

2.4.4.1 Pump & Treat processes

Pumping groundwater to the surface is a strategy which is intended to contain contamination in the subsurface by hydraulically preventing groundwater from flowing out of the contaminated zone. Although pumping and treating groundwater may result in partial remediation of soil and groundwater in the saturated zone, this approach should not be seen as a way to completely remove contamination from the saturated zone. In some cases the pump and treat option is the only one available or is less expensive than other options even if groundwater has to be pumped for many years.

The major advantage of pump and treat is that conventional technologies for water and wastewater treatment can be applied for decontamination of the pumped groundwater. These include biological treatment, activated carbon adsorption, air stripping of volatiles, and metal precipitation. Pump and treat is most effective when it is combined with measures of isolation and/or removal of the contamination source, in order to prevent further contaminant introduction into the groundwater [107]. The flowchart in Figure 33, page 51, shows a sequence of steps for treating extracted groundwater which includes all of the general types of treatment. Obviously, most treatment systems will not utilize all of these processes but may use as many as three of them in series [80].

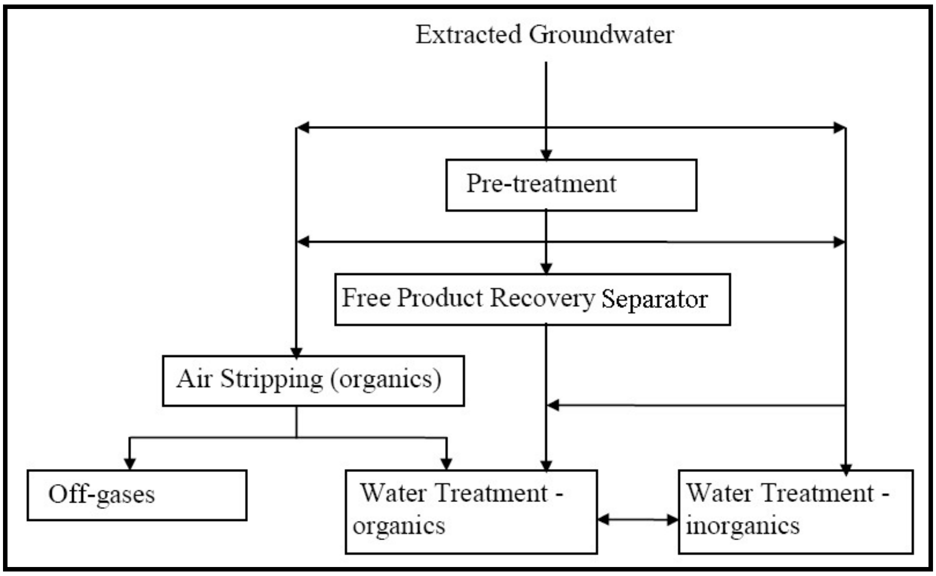


Figure 33. Sequence of possible steps for treating extracted groundwater [80].

a) Free product recovery

Separators are used to recover free products from extracted groundwater and are limited to separating immiscible phases from water. This process relies on the density difference between water and recoverable free product to separate the two fluids. They are used extensively to separate refined petroleum products, such as oil and gasoline, from water. A separator is usually comprised of a tank with baffles to prevent short-circuiting. Extracted groundwater enters at the top of one end of the separator and separated oil is skimmed off the top, while treated water leaves at the bottom of the other end. The separated oil may be recycled, or destroyed in incinerators [80].

b) Pre-treatment of extracted groundwater

To achieve the water quality required by a treatment technology, a pre-treatment system may consist of one or more of techniques listed below:

- **aeration:** air is used to oxidize dissolved iron and manganese to produce inorganic precipitates.
- **chemical oxidation:** oxidizing agents such as hydrogen peroxide (H_2O_2), chlorine dioxide (ClO_2), and potassium permanganate ($KMnO_4$) convert dissolved iron and manganese to inorganic precipitates.
- **pH adjustment:** acids and alkalis adjust the pH to achieve water quality required by the treatment technologies.
- **filtration:** filters remove suspended solids already in extracted groundwater and inorganic precipitates formed during aeration and/or chemical addition.
- **water softening:** chemicals remove hardness from extracted water.

c) Ex-situ groundwater bioremediation

This well-developed technology has been used for many years to treat municipal wastewater. As a result, equipment and materials are readily available. Bioreactors are designed to bring contaminants dissolved in extracted groundwater into contact with micro-organisms which may be suspended or attached to a medium. The process is classified as suspended growth systems (e.g. activated sludge processes), or fixed film reactors (e.g. trickling filters or rotating biological contactors). Attached and suspended systems are often used together.

In suspended growth systems, contaminated groundwater and a microbial population present in activated sludge are mixed in an aeration basin. The micro-organisms degrade the contaminants aerobically, and produce new cells at the same time. In fixed film (attached growth systems) such as trickling filters and rotating biological contactors (RBCs), the microorganisms are attached to a solid medium. Common components in aerobic systems include one or more reaction chambers containing bacteria, clarifiers to remove solids and bacteria, and associated piping and distribution systems.

Bioreactors are used mainly to treat non-halogenated volatile and semi-volatile organics and fuel compounds. According to [110], this technology is best used for lower molecular weight, highly soluble compounds such as aromatics at Total Organic Carbon (TOC) levels of < 5,000 mg/L. At these levels, removal efficiency can be greater than 99%. Factors such as temperature, concentration of the contaminant, nutrient levels, and residence time influence how the technology performs. Treated water is discharged to sanitary sewers, or may require polishing to achieve drinking water standards.

d) Carbon Adsorption

Adsorption by “activated” carbon is not a new technology, having had a long history for treating municipal, industrial and hazardous wastes. Activated carbon is an extremely good adsorber of organic chemicals. When extracted groundwater is pumped through a series of canisters containing activated carbon, dissolved organic compounds adsorb onto the carbon. Components common to most systems contain one or more canisters in series, piping and distribution components, and a backwash system. Once carbon in the canisters has been saturated with contaminants, the carbon has to be replaced or regenerated thermally. This physical, non-destructive process may achieve low levels of contaminants in effluents and is frequently used as a polishing step to reach drinking water standards.

For carbon adsorption from the liquid phase, target contaminants are halogenated and nonhalogenated semi-volatile organic compounds. The technology is less effective for treating halogenated volatile organic compounds, fuel hydrocarbons, pesticides, and inorganics. The Canadian Petroleum Products Institute [110] reports it is best suited for low levels of hydrocarbons (up to 1,000 µg/L), and that it achieves 99% removal efficiency at these levels. In addition to removing organics, the carbon has an excellent potential to adsorb some metals like arsenic, chromium, tin, mercury and silver.

e) Oxidation / Reduction

Oxidation is often used to remove iron dissolved in groundwater. At pHs between 7.0 and 7.5, ferrous iron is easily oxidized to insoluble ferric iron. As mentioned in the section on pre-treatment (b), the water can simply be aerated to convert the ferrous iron to ferric iron. Iron is not a toxic metal but is considered to be a nuisance inorganic because of its negative impact on some systems used to remove other constituents from extracted groundwater.

Unlike iron, hexavalent chromium is a toxic heavy metal. Like ferrous iron, it is soluble in water at high pHs. Treatment takes advantage of the fact that trivalent chromium is not soluble at high pHs, and consists of first lowering the pH of contaminated water to below 3.0. Next, a chemical reducing agent like sulphur dioxide converts the hexavalent chromium to the trivalent form. When the pH is raised again, the trivalent chromium precipitates. Chemical reduction is also used to remove lead and mercury. Oxidation and reduction can be carried out using simple, available equipment and reagents. Capital and operating costs are low and the process is easy to implement. Capital costs for oxidation and reduction include costs for storing chemicals, mixing chemicals and feeding them into the treatment system.

2.4.4.2 Air Sparging

Air sparging is a remediation technology used frequently for subsurface removal of dissolved volatile organic contaminants VOCs and nonaqueous phase liquid NAPL contaminants. Air sparging has been shown to be effective in removing several types of contaminants with relatively high Henry's Law constants ($K_H > 10^{-5}$) such as the lighter petroleum compounds (C_3–C_{10}) and chlorinated solvents [111],[112],[113]. Also, contaminants with larger aqueous solubilities and high K_H will be more readily removed because of their propensity to desorb from soil particles into the aqueous phase and subsequently diffuse to sparging air channels [114],[115]. Air sparging involves injection of air into the subsurface below the water table. Injected air traverses horizontally and vertically in channels through the soil column, creating an underground stripper, known as the radius of influence (ROI), around each injection point that removes volatile and semivolatile organic contaminants by volatilization. The airflow is controlled by the forces of buoyancy and capillarity, and by the influence of permeability. Disolved or NAPL-phase organic contaminants partition to the air phase and are carried to the vadose zone. Soil vapor extraction (SVE) usually is implemented in conjunction with air sparging to remove the generated vapor-phase contamination from the vadose zone. Oxygen added to the contaminated groundwater and vadose-zone soils also can enhance biodegradation of contaminants below and above the water table. Airflow generally occurs in small air channels at the pore scale, although bubble flow is possible in well-sorted, coarse-grained media (e.g. gravel) [81],[116],[117].

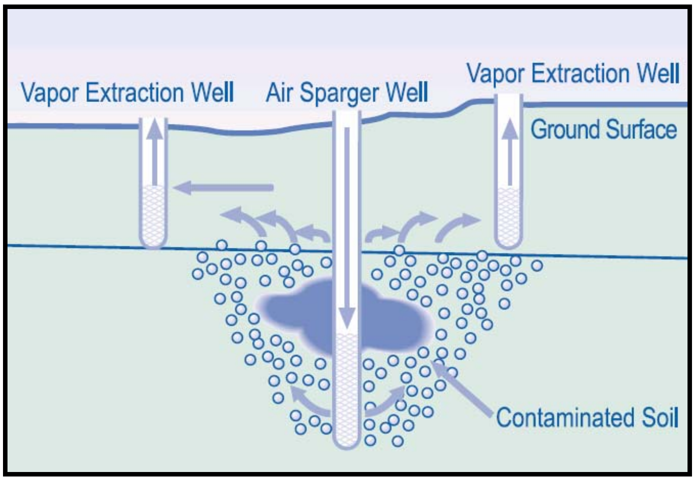


Figure 34. Model of an air sparging system [81].

Characteristics of the porous medium have significant effects on contaminant removal and system design factors. In air sparging, airflow distributions are directly impacted by air permeability, which is a function of particle size and distribution. Air channels, likely only a few grain sizes in diameter and formed by the injected air, make up the extent of the ROI. These air channels take the path of least resistance (lowest capillary pressure) through the porous media, avoiding areas of lower permeability. To impact the lower permeability regions, higher air entry pressures are applied [115],[118],[119].

For contaminant vapor movement, increases in porosity and moisture content decrease the gas movement rate. VOC vapor movement will be greatest through dry, highly permeable sand or gravel and slowest through clay and wet soils, as water may reduce the contact area between the VOC and air. Furthermore, lower permeability soils tend to have a greater capacity to adsorb contaminants because of the higher surface area to volume ratio and greater amounts of organic carbon content usually associated with such soils. Therefore, in a heterogeneous aquifer, there can be a tendency for the majority of VOCs to be located in the areas with the least permeability, which are also least touched by sparging induced air channels, thus the most difficult to remediate [115],[120],[121]. During air sparging, mass transport is the primary mechanism controlling contaminant removal. At the onset of sparging, contaminant mass removed is mostly from the evacuation of vapors in the soil pore space on the unsaturated zone in equilibrium with the surrounding organic contaminant followed by advective and dispersive/diffusive transport of contaminant from the surrounding aqueous phase to the ROI. Diffusive transport can be limited by slow mass-transfer from immobile non-aqueous phase liquids (NAPLs) to the advecting aqueous and gas phases, as well as from areas of low permeability within the aquifer. Contaminant removal through air-sparging induced biodegradation is secondary to vapor removal [124],[125].

2.4.4.3 Air Stripping

For In-Well Air Stripping, air is injected into a double-screened well, causing the volatile organic compounds in the contaminated groundwater to transfer from the dissolved phase to the vapor phase in air bubbles. As the air bubbles rise to the surface of the water, the vapors are drawn off and treated by a soil vapor extraction (SVE) system.

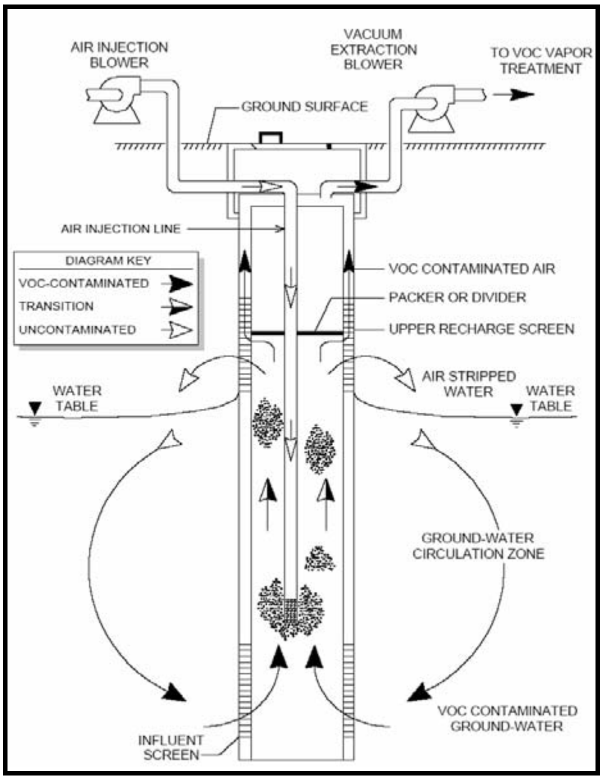


Figure 35. Schematical representation of air stripping [126]

2.4.4.4 Permeable Reactive Barriers

Treatment walls, or permeable reactive barriers (PRB, Figure 36), involve construction of permanent, semi-permanent, or replaceable units across the flow path of a dissolved phase contaminant plume. As the contaminated groundwater moves passively through the treatment wall, contaminants are removed by physical, chemical and/or biological processes, including precipitation, sorption, oxidation/ reduction, fixation, or degradation. PRB may contain agents placed either in the path of contaminant plumes to prevent further migration or immediately downgradient of the contaminant source to prevent plume formation [127].

The funnel and gate system (Figure 37) is one application of a permeable reactive barrier for in situ treatment of dissolved phase contamination. Such systems consist of low hydraulic conductivity cut-off walls (e.g., $1x10^{-8}$ m/s) with one or more gaps that contain permeable reaction zones. Cut-off walls (the funnel) modify flow patterns so that groundwater primarily flows through high conductivity gaps (the gates). The type of cut-off walls commonly used are slurry walls, sheet piles, or soil admixtures applied by soil mixing or jet grouting. The wall or gate is constructed as a grouted screen or construction element consisting of a geotextile casing (geotextile caisson) with a central filling of filter sand with added sorptive minerals like Na-bentonite, pillared clays, natural zeolites, fly ash zeolites or zero-valent iron from recycled cast iron fillings and activated carbon. Funnel-and-gate systems can be installed at the front of plumes to prevent further plume growth, or immediately downgradient of contaminant source zones to prevent contaminants from moving into plumes [127],[129],[130],[131],[132].

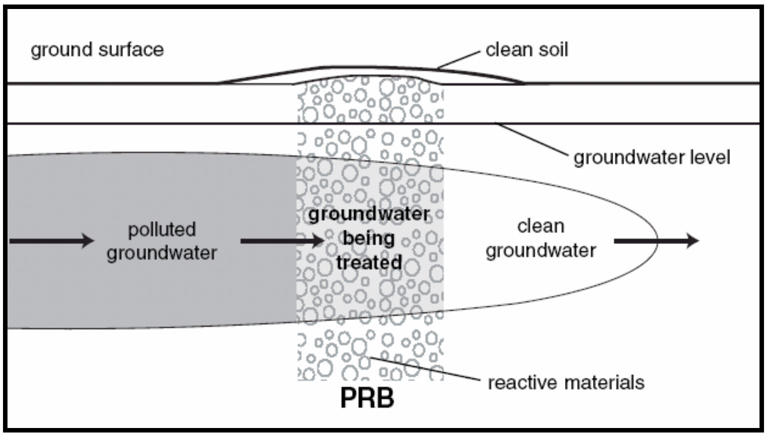


Figure 36. Model of a Permeable Reactive Barrier [128].

The funnel and gate system is aimed at cleaning up in situ contaminated aquifers. In situ remediation, for instance, works in the case of biodegradable organic molecules as contamination or in the case of zerovalent iron as reductive processes. Zero-valent iron can be beneficially used for the dechlorination of CHC. However, Cl-containing metabolites may be formed [122],[123]. In the case of heavy metals, the reaction wall (e.g. geotextile with zeolites) concentrates the contaminants, and the geotextile has to be removed for further treatment [130].

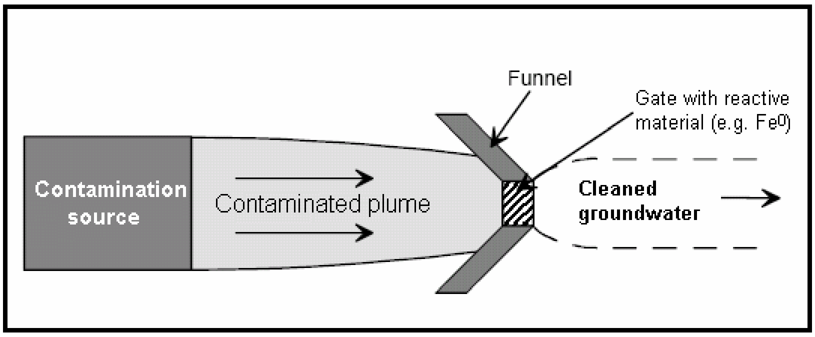


Figure 37. Plan view of a "funnel and gate" system [133].

A similar concept to the funnel and gate system is the “funnel and reactor” concept. For this process, instead of a passive reactive wall, a reactor is introduced, as it can be observed in Figure 38. If this reactor is planned to operate underground and no pumping of the groundwater takes place, the entire system can be passively operated. On the other hand if the use of pumps is necessary to operate the reactor on site, the passive character of the overall system is no longer fulfilled for this configuration [133].

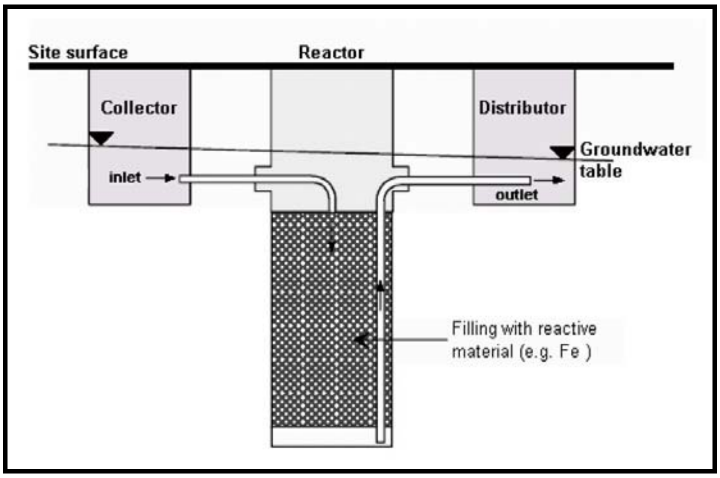


Figure 38. Elevation view of a funnel and reactor system for groundwater remediation [133].

2.5 Redevelopment of contaminated sites

Cleanup and reuse of fallow lands and contaminated sites offers the obvious benefit of improving environmental quality and removing or reducing the threat to public health. By redeveloping disturbed land, it is possible to slow the consumption of undeveloped lands or “greenfields”. Greenfield development results in the loss of farmland and open space, worsens existing traffic problems and may lead to more water and air pollution [134].

Land consumption, i.e. the conversion of (predominantly used) agricultural areas in residential and traffic areas, is directly connected with soil impairments and soil loss. Nevertheless, the land consumption for residential purposes in the EU has had a continuous growth over the years. The residential areas in many EU countries annually grow by approximately 1 to 1.5 % (see Figure 39 and Figure 40). Moreover, economic expansion and industrial growth are met with growing lack of industrial sites. The supply of new building sites is limited and must contend with other competing uses, such as housing, recreation, nature, traffic, or agriculture [47],[137]. Thus, the clean-up and reuse of former contaminated sites can be a meaningful alternative to address this issue, as most contaminated sites are located in metropolitan centers and are, therefore, prime candidates for urban development.

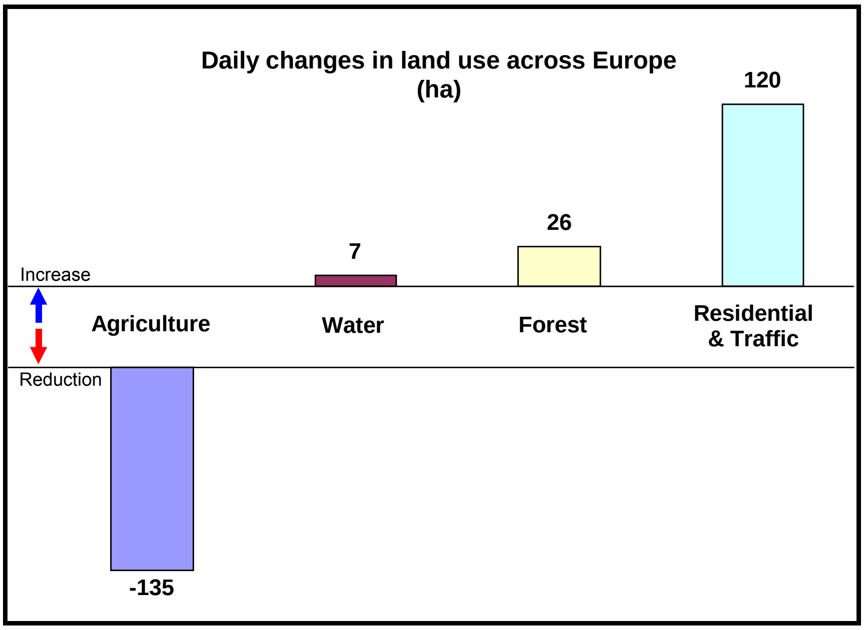


Figure 39. Daily changes in land use across Europe [135].

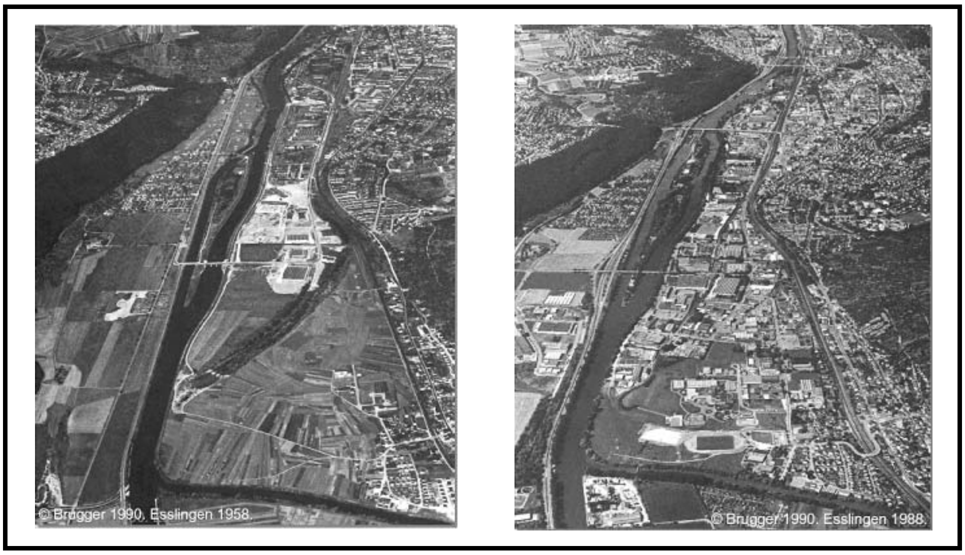


Figure 40. Urban sprawl, overview of urbanization in flooding zones in the city of Essingen (Germany) [136].

In Austria, although the redevelopment of contaminated sites stands as an interesting alternative, a series of technical, juridical and organizational obstacles have made this option real only in a handful of cases (Figure 41), and unfortunately, in a more or less non-systematic random way [138].

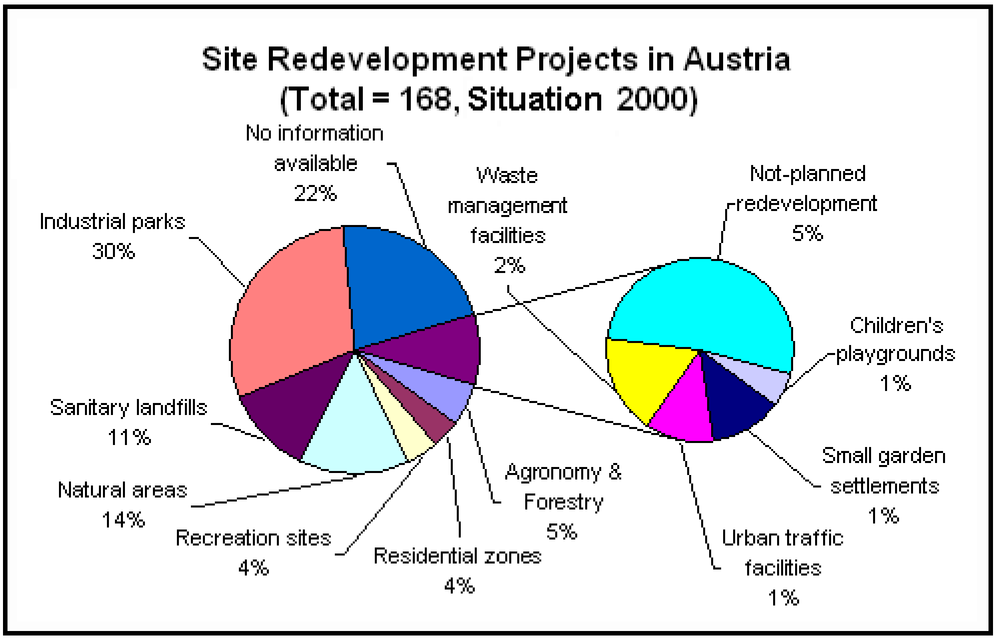


Figure 41. Summary of the site recycling projects carried out in Austria (adapted from [139])

The land consumption by construction areas in Austria adds up to 10 - 20 ha/day, whilst 5.8 ha/day for traffic. That means a consumption of 7 - 12 m^2/year per inhabitant [140]. Current data for annual area requirements for housing, commerce and traffic are reported with 2,272 ha/year, i.e. 6.2 ha/day. In comparison 1,100 ha of trade and industrial lands fall in disuse annually in Austria [141],[142],[143]. This would mean that, with unrestricted surface redevelopment, ca. 48 % of the needed surfaces could be covered by fallow areas.

A considerable fraction of shut down commercial areas does not fall out of the economic cycle, but in some cases are reused even without external support. For these “self-runners” the relationship of reuse potential and market obstacles is classified in such a favourable manner that even possible complications are taken by in the purchase. If this relationship worsens, the recycling gets more complicated, because the reuse costs include possible remediation costs that cannot be covered by the expected utilities of the new use. However, this condition is not static, as both the reuse potential and market obstacles may be changed by external influences; for example, land conversion and new traffic routes, and changes of the legal conditions and risk minimization, respectively.

Site recycling projects are influenced by several external factors, such as its previous use, pollutant inventory, remediation method, expected new use (redevelopment), financing and project organization. If the surface recycling to date projects published in Europe are analyzed, it is possible to observe the following facts [143],[144]:

- the most common pollutants have an organic nature; nevertheless, heavy metals have an important role in soil pollution as well.
- in approximately half of the cases, a commercial/industrial redevelopment took place, followed by housing and other uses.

- although a connection between location size and remediation costs could be in principle recognizable, for sites under 50 ha such correlation lacks of significance.
- in half of the cases the financing has taken place partly or completely via the public hand, only in 25 % via a private investor. Also, in 50 % of the cases the public hand was entrusted organizationally, or it was merged with the project development [145].

The participants (i.e. stakeholders) of a surface recycling project have different interests according to their position within the redevelopment program. As stakeholders one can identify the ones presented in Figure 42. In practice it is often the case that stakeholders take part in several functions of the project, and thus interest conflicts arise. It is therefore the task of the project organization to solve such conflicts successfully. Redevelopment in the sense of surface recycling aims at the reactivation and reutilization of properties whose land development or soil condition demand containment and/or remediation measures for a concern-free utilization.

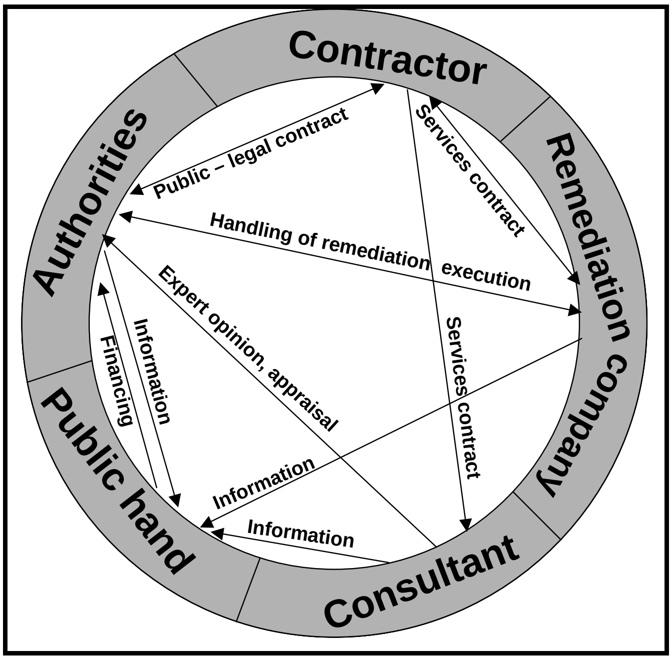


Figure 42. Participants in a redevelopment project and their interrelations [146].

Surface recycling is therefore the reintegration of areas that have lost its past function and use in the economic and nature cycle, by means of environmental, technical and politic-economic measures. Among others, sites like shut down commercial and industrial complexes, military real estate properties as well as traffic surfaces and old deposits are of special concern [137],[143]. The reuse of contaminated industrial lands in the German-speaking region lays both in public and private interests, as it brings direct economic and indirect social as well as direct social advantages. By financing the economically justified expenditure through private investors, the public hand investment can be reduced to the economically necessary extent. Regarding the location development potential, high-quality surfaces can be reused by new operating settlements or communal mechanisms. These surfaces are usually fully technically developed in terms of both traffic and infrastructure (water, waste water, electricity), which determines considerable savings when compared with settlements on green areas. In relation to the classical site remediation, in redevelopment projects there are a series of supplementing requirements to be considered, such as the cost and liability risks, insufficient planning and legal security as well as high time and administration expenses.

2.6 Decision-making theory and decision support systems

The term “decision support system” refers to an approach that integrates decision maker's own insights with computer's information processing capabilities for improving the quality of decision making [147],[148]. This approach also involves an integration of data from a variety of sources. However, these systems do not automate management decisions simply by finding optimal solutions to a problem. The final selection of management alternative is left to the user [148],[149],[150]. The approach to taking decisions on the management of land contamination has changed markedly over 30 years. Change has been rapid with policy makers and regulators, practitioners and researchers having to keep pace with new technologies, assessment criteria and diagnostic methods for their measurement, techniques for risk analysis and the frameworks that support decision-makers in their efforts to regenerate historically contaminated land [151].

The following section presents the decision-making theory and the way it has been considered as an important management tool in many branches of engineering. The introduction of decision making tools to projects dealing with the management of contaminated sites is described as well.

2.6.1 Introduction to decision-making theory

Classical decision theory is developed within economics and forms the main theory of decision making used within operations research. It conceptualizes a decision as a choice from a set of alternative actions. The relative preference for an alternative is expressed by a utility value. A decision is rational when it maximizes expected utility [152].

Knowledge-based systems (KBS) consist of a high level conceptual model in terms of knowledge and goals of an application domain, such as the medical or legal domain, together with a reusable inference scheme for a task, like classification or configuration. Moreover, knowledge-based systems focus less on the definition of the optimal decision represented by the decision rule, but instead also discuss the way decisions are reached. They are therefore sometimes identified with theories of deliberation instead of decision theories. However, in classical decision theory the way to reach optimal decisions has also been studied in decision theoretic practice called decision analysis [153]. Nowadays there exists an overall consensus that the process of building a KBS may be seen as a modeling activity. Building a KBS means building a computer model with the aim of realizing problem-solving capabilities comparable to a domain expert. It is not intended to create a cognitive adequate model, i.e. to simulate the cognitive processes of an expert in general, but to create a model which offers similar results in problem-solving for problems in the area of concern. While the expert may consciously articulate some parts of his or her knowledge, he or she will not be aware of a significant part of this knowledge since it is hidden in his or her skills. This knowledge is not directly accessible, but has to be built up and structured during the knowledge-acquisition phase. Therefore, this knowledge acquisition process is no longer seen as a transfer of knowledge into an appropriate computer representation, but as a model construction process.This modeling view of the building process of a KBS has the following consequences [152]:

• Like every model, such a model is only an approximation of the reality. In principle, the modeling process is infinite, because it is an incessant activity with the aim of approximating the intended behaviour.
• The modeling process is a cyclic process. New observations may lead to a refinement, modification or completion of the already built-up model. On the other side, the model may guide the further acquisition of knowledge.
• The modeling process depends on subjective interpretations of the knowledge engineer.

Therefore, this process is typically faulty and an evaluation of the model with respect to reality is indispensable for the creation of an adequate model. According to this feedback loop, the model must, therefore, be revisable in every stage of the modeling process. Gregory and Clemen [154] lay out eight themes as elements of good decision-making (Table 11). These themes represent fundamental principles from decision analysis [155],[156]. As such, they reflect a sound and consistent approach to decision making that has the credibility of years of research in fields as diverse as economics, statistics, and psychology.

Table 11. Eight decision-making themes according to Gregory and Clemen [154].

Decision making themes	
- Establishing the decision context	- Quality of information
- Identifying values	- Creating alternatives
- Understanding uncertainty	- Making tradeoffs
- Structuring consequences	- Group negotiations

The eight decision themes begin with the definition of the problem and the establishment of a *decision context*. Recognizing that a decision opportunity exists and identifying the key players in the decision process is the essence of defining the context.

Uncertainty affects the probable occurrence of various *consequences*, and students are encouraged to think about the distinction between resolvable and unresolvable sources of uncertainty. Decision trees are introduced as a powerful visual and analytic tool for relating consequences to decision opportunities and chance events. Asking questions about the *quality of information* can help to refine consequence estimates, resolve inconsistencies, and search for disconfirming evidence. The combination of clearly structured values and relevant information can lead to *creative alternatives*, each of which may have strong and weak points, thereby highlighting the *tradeoffs* inherent in the different alternatives.

When a problem involves multiple stakeholders, those stakeholders' values must be considered in *negotiating* a decision. Diversity of values among stakeholders is not only expected but can form the basis of a joint decision that is mutually agreeable to all parties. The key to this approach to decision making lies in its emphasis on understanding ones own values and objectives. In an important sense, an emphasis on values empowers the individual decision maker; the only expert about anyone's values is that individual. At the same time, the approach is humbling because it makes clear that decisions, values, uncertainty, and consequences relate to many people, some close to the decision maker (family and friends), but also to others without any relationship with him (as the society in general). Good decision making requires care and responsibility in understanding the network of interests that surround us and define the decision opportunities we face [157].

2.6.2 The Logical Framework Approach

The Logical Framework Approach (LFA) is a specific planning methodology that can be used to prepare many different types of projects, including environmental investment projects. The output of LFA is the Logical Framework Matrix (LogFrame). The use of LFA is required by many international financing institutions (such as the World Bank) and is obligatory for projects funded by EU financial assistance programmes. In other words, each project proposal for EU financial assistance must be presented in the form of a LogFrame. The reason for this is that LFA is a very useful methodology for project design and preparation. A properly prepared LogFrame is an easy-to-read summary of the project proposal, describing the key logical links and project parameters [163]. LFA can be used throughout the activity management cycle in:

- identifying and assessing activities that fit within the scope of country programs;
- preparing the project design in a systematic and logical way;
- appraising project designs;
- implementing approved projects; and
- monitoring, reviewing and evaluating project progress and performance.

LFA is best started early in the Activity Cycle but the same analytical tools can be used to help review and restructure ongoing projects which have not previously been designed using LFA principles. As LFA is an 'aid to thinking', it has widespread and flexible application [164]. In general, the Logical Framework Approach (LFA) consists of two main phases, namely analysis and planning phases. The analysis phase consists of stakeholder, problem, objective, and strategy (scenario) analyses. Planning phase is composed of project structuring, formulating measurable indicators, and risk and sensitivity assessment [165].

Stakeholder Analysis: In order to maximize the social, economic, environmental and institutional benefits of the remediation and minimize its negative impacts, it is extremely important to develop a comprehensive picture of the interest groups, individuals and institutions that take part in the DA at hand.

Problem analysis: Main purpose of problem analysis (PA) is to create a better understanding of the decision problem. PA involves two tasks: to identify the major problems faced by the beneficiaries, and the development of a problem tree to identify causal relationships between the various problems.

Objective analysis: If problem analysis presents the negative aspects of the current situation, the *analysis of objectives* presents the positive aspects of a desired future situation. This change of perspective involves the reformulation of problems into objectives that define what the project should achieve for its intended beneficiaries. During analysis of objectives the potential solutions for a given situation are identified drawing up an objective tree [165].

Formulation of measurable indicators: Resulted sub-objectives at the bottom level of the tree must be measurable. To ensure this, the sub-objectives must be accompanied by *indicators,* which specify the information required about achieving progress in development options. An indicator may be defined as a parameter or a value derived from parameters, which provides information about a phenomenon. The indicator must simplify the phenomena in order to help to understand complex realities by providing information about changes in a system [166]. The utility of the information provided by a certain indicator is absolutely dependant on the context in which the indicator is used. Their selection is therefore a crucial aspect of environmental assessment, and should follow a careful selection process [167]. Indicators possess a synthetic meaning and are developed for a specific purpose (Table 12).

Table 12. Definition of terms used in environmental performance assessment [168].

Term	Definition
Indicator	A parameter or a value derived from parameters, which points to/provides information about/describes the state of a phenomenon/environment/area with a significance extending beyond that directly associated with a parameter value.
Index	A set of aggregated or weighted parameters or indicators.
Parameter	A property that is measured or observed.
Indicators of environmental conditions	They comprise environmental quality and aspects of quantity and quality of natural resources.
Indicators of environmental pressures	They describe pressures on the environment caused by human activities.
Response indicators	They describe the changes only from a societal point of view, not considering the ecosystem.
Indicators for use in performance evaluations	Selected and/or aggregated indicators of environmental conditions, indicators of environmental pressures and indicators of societal responses for the purpose of environmental performance evaluation.
Environmental indicators	Comprise all types of indicators, i.e. indicators of environmental pressures, conditions and responses.

When using indicators, the following points must be considered [168]:

- Indicators provide only a tool for evaluations and need to be supplemented by other qualitative and scientific information in order to avoid misinterpretation. Such information is particularly needed to explain driving forces behind indicators changes, which form the basis for an assessment.
- Indicators must be reported and interpreted in the appropriate context, taking into account the ecological, geographical, social, economic and structural features of countries or regions.

2.6.3 The Balanced Scorecard and its application to engineering

The selection of an appropriate technology is a crucial activity in a remedial project, where technical, economic, social, legal and environmental goals and objectives must be considered and evaluated. An important aspect of site remediation projects is the fact that each site must be evaluated individually and also that the allocation of funds, normally scarce or limited, must be performed rationally among all "competing sites" that are evaluated for remediation. General and local factors such as the intended reuse of the property, the hydro-geological conditions of the site and the type of contamination present can be generalized to some extent, and can be the basis for technical decision-making systems. Nevertheless, there are local parameters that can not be generalized and that play an important role in the decision-making process, such as the social condition and the regional development priorities of the society surrounding the contaminated area. A decision-making strategy must fulfil all the fore mentioned requirements in order to be considered an integral approach for the search of revitalizing a contaminated site. For that reason, the strategy for selecting the appropriate remedial option for contaminated sites is still considered as the most poorly planned part of restoration projects [6],[80]. The balanced scorecard (BSC) is a measurement-based strategic decision support system that provides a method of aligning activities to the strategy and scoring of multidimensional sectors of goals achievement, as presented in Figure 43 [158],[159].

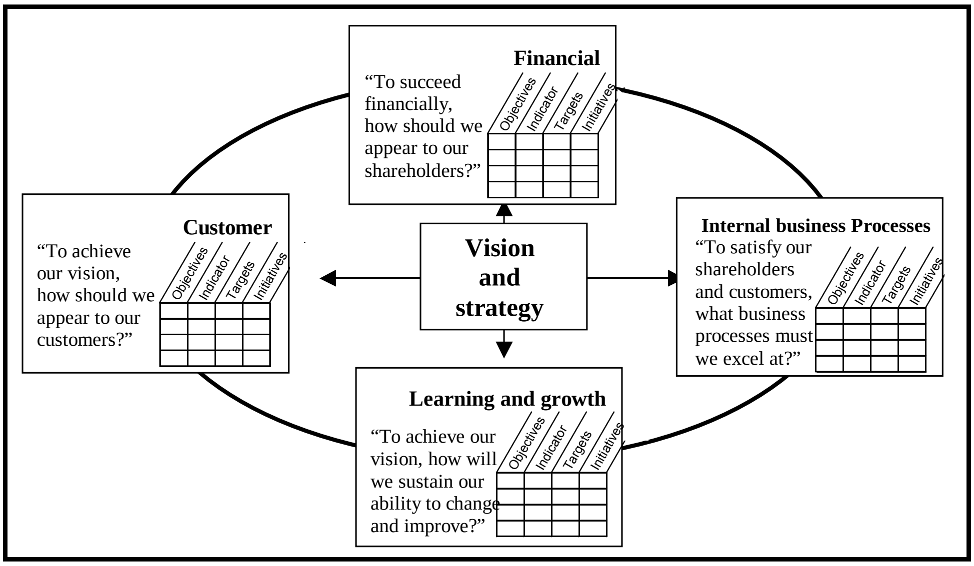


Figure 43. The BSC framework [158].

Originally intended for orienting companies on their future financial measures to ensure good short-term financial results as well as to achieve their strategic results, this strategy has been wide-spread to all management activities in companies as well as in activities where strategic planning is intended [144],[160],[161]. Decision analysis (DA) is a multidimensional process that involves participants from various fields and contains structural work steps. DA is limited by the decision context (DC), which is the setting where the decision takes place. DC is limited by the administrative, political and social structures that surround the decision under consideration, and specified by the activity into consideration. An overview of the different factors affecting DA is shown in Figure 44 (page 66). Moreover,

- Decision context and corresponding fundamental objectives are closely related and they frame the **decision situation**. Clearly the objectives are different from the situation when considering different career opportunities.
- By defining the decision context and establishing the nature of the decision problem carefully, the treatment of the real problem can be ensured.
- A careful specification of the decision context is particularly relevant if several DMs or stakeholders are involved in the decision analysis process. Without a mutual agreement on the decision context problems are likely to occur in subsequent phases.

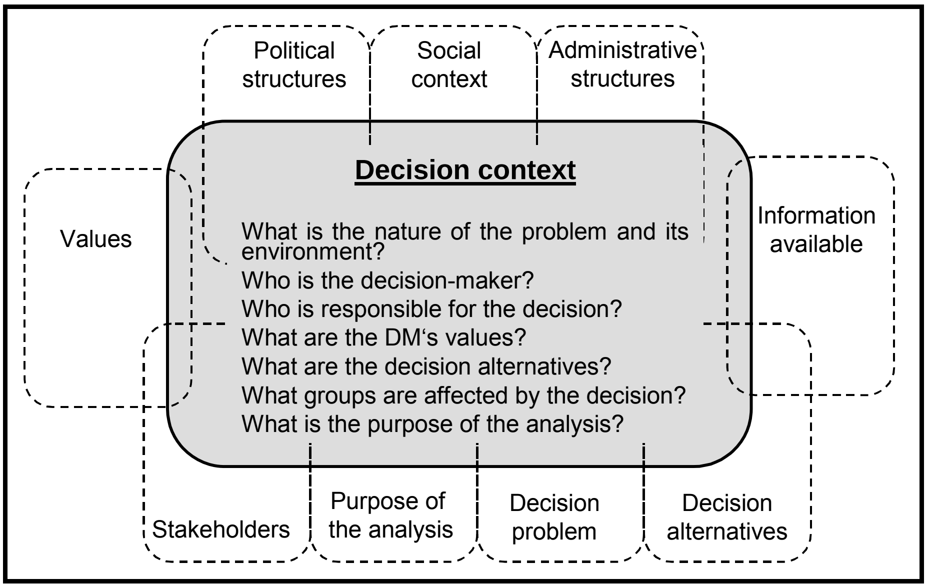


Figure 44. Decision context for a general decision analysis [162].

As participants of DA it is possible to identify *stakeholders*, possible *decision-makers* and *decision analysts*, all of which are defined as follows.

- A **stakeholder** is a person or a body with an interest in the decision.
- A **decision-maker** (DM) is a person, organisation or any other decision-making entity, empowered to make decisions concerning the decision-making problem at hand. In most cases the DM is also responsible for the decision and possible consequences.
- A **decision analyst** provides insight and advice to the DM in difficult decisions. His / her task is to help the DM to find the most appropriate decision alternative(s) with possible reasoning and facilitate the decision-making process.

Possible relations between the different parties of a DA process are described in Figure 45; page 67. It is worth noting that:

• Some key players are not necessarily included in the analysis. For example, it might take a considerable effort to identify all the stakeholder groups that may have only a little relevance to the decision análisis process (Figure 45 B).

• The roles of the DM, analyst and stakeholder may overlap. That is, they can partly represent the same body (Figure 45 C), or may even be a single person (Figure 45 D).
• As Figure 45 shows, the analyst can be a separate person, or body, or the DM can act as an analyst herself / himself.

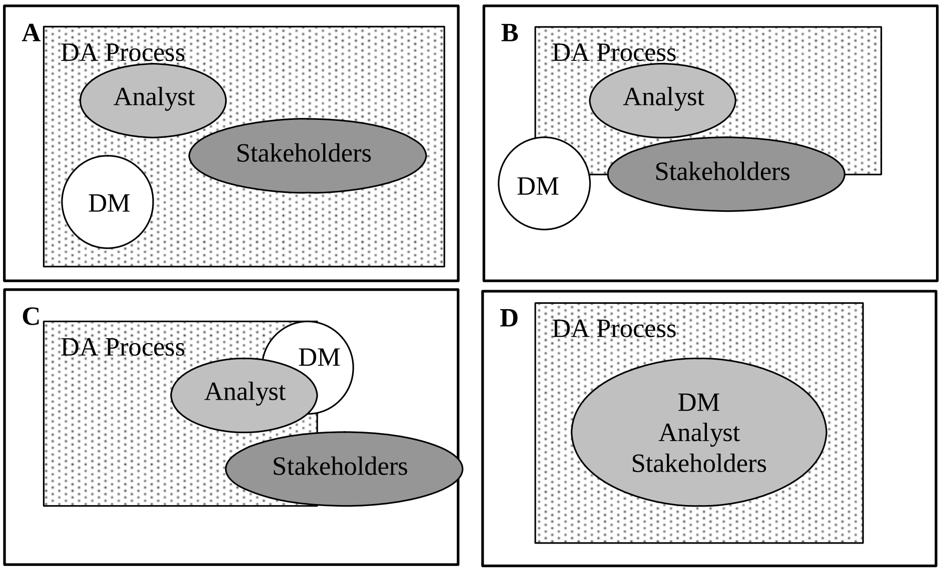


Figure 45. Possible relationships among the participants of a decision analysis [162].

For the implementation of a BSC within the context of site remedial projects, the LFA approach (as described in chapter 2.6.2) can be suggested. Nevertheless, there are further steps to be taken, which imply the involvement of the stakeholders, the analyst and the DM:

Weighting of goals: Weights of the objectives are used when interpreting the results of the analysis. For example, how much the DM weighted the environmental and economical factors in the aggregate. There are two ways to determine weights in a goal tree: Non-hierarchical weighting, in which weights are defined for the attributes only, and Hierarchical weighting, where weights are defined for each hierarchical level separately, and then multiplied down to get the corresponding lower level weights. In non-hierarchical weighting upper-level weights (objective weights) are not asked, but they can be calculated as a sum of the lower level weights. In the additive value model, only the attribute weights are used for determining the overall value of the alternatives [162].

Normalization of indicators: Environmental indicators are specific measurements identified as strategically important to the success of the environmental program. There is a strong preference in selecting numerical indicators, which can measure more subtle changes in performance than qualitative indicators. However, a numerical indicator is only meaningful when we understand the significance of the measurement in context. Normalization is the most common approach to assessing indicators and is done by identifying a second number that can be used to establish a ratio to an indicator [169]. An appropriate process consists in normalize each indicator against subjective utility functions which result in dimensionless values (e.g., values from 0 to 10). The definition of such dimensionless utility scores is an essential aspect in the formulation and structuring of the BSC [170].

Scenario analysis: Starting with the famous book of Kahn and Wiener [171] scenario analysis became a major decision tool, e.g. in management, economics, and environmental decision-making (see, [172],[173],[174]) [175]. The expression of a small number of scenarios, which represent plausible future environments, is a well-recognized method in the planning process. Scenarios induce participants to think through the consequences of decisions and actions. Forecasts are often wrong when dealing with the macroenvironment [176]. Scenarios, instead, try to highlight the reasoning underlying a forecast with explicit attention to sources of uncertainty. Scenario analysis focuses the attention of the decision makers on a set of different descriptions of the future, which are explicitly designed to be feasible, although not necessarily the most likely [177].

Sensitivity assessment: The aim of the sensitivity analysis is to explore how changes in the model influence the decision recommendation. If a small change in one or several aspects of the model causes the recommended decision to change, the decision is said to be sensitive to those changes. Recognising the aspects to which the decision is sensitive enables the DM to concentrate on, or possibly reconsider the issues, which may cause changes in the decision. Any part of the decision analysis process, from the identification of the decision problem to the evaluation of the preferences, can be subjected to the sensitivity analysis. After the sensitivity analysis the DM may return to earlier phases of the DA process; new alternatives may be identified, model structure may be changed etc. Thus, sensitivity analysis is a central part of the decision analysis cycle [162].

2.7 Synopsis of Chapter 2

After the introduction of the motivation and the goals for this work in Chapter 1, this chapter presents the framework to which contaminated sites management projects are subjected. A summary of the legal context in Austria is presented, as it introduces the definitions and regulations that form the basis for this study. The technological alternatives for managing contaminated sites have been summarized in a state-of-the-art review of identification and evaluation procedures for sites under suspicion as well as technologies for the containment, remediation and redevelopment of contaminated sites. Finally, the basics of decision making theory have been introduced. This chapter stands therefore as the basis for the development of the proposed knowledge-based tool, which is described in the following sections.

3 Methods and practical approach

The previous section provided a description of the legal, technical, economic and environmental aspects that are to be considered in site remediation projects. Considering all of these aspects, Chapter 3 presents at first the proposed strategy to develop a knowledge-based tool for contaminated sites management.

The developed tool comprises the experience in Europe and the U.S.A. for the evaluation, remediation, containment and further management of contaminated sites. By considering the state-of-the-art technologies for the management of derelict areas and some already proven methods for risk assessment of sites on the human health and environment, this tool stands as a novel approach for the selection of the most appropriate alternative to carry out in a remedial project of an individual contaminated area.

The developed strategy includes a risk assessment evaluation, a selection procedure for the identification of feasible technologies and their combinations as alternatives for the management of the evaluated site, and finally a procedure for the selection of the most appropriate technology for the individual study case. Each step of the proposed system is then described in detail. Finally, Chapter 3 describes the work carried out with the University of Concepción and the Chilean National Environmental Commission to establish the first land register of (suspected) contaminated sites in an industrial Chilean Region, basis for the determination of the actual contaminated sites situation.

3.1 Selected strategy for the implementation of a decision support tool for contaminated sites management

In general, the most poorly planned part of site remediation projects is the decision-making strategy. The reasons for this are numerous but the main ones are that decision-making is not ranked as a high priority task by most project planning teams and that decision-making methods are poorly understood in general. Most project managers and planning teams tend to focus primarily on the choice of specific technology instead of on all of the general options for remediating the site. Many projects involve no decision-making at all because the remedial alternative has been pre-determined by either the site owner or the general contractor. There are numerous acceptable methods for making decisions. After a site assessment has been completed, a three step process can be recommended [80]:

Step I: Set Cleanup Goals and Criteria

- Ensure that the site contamination is completely characterized;
- Determine regulatory requirements and criteria and involve appropriate government regulators and approval personnel in the planning;
- Determine technical, spatial and temporal restrictions;
- Determine the overall goal of the project and the site- specific cleanup criteria.

Step II: Screening of Alternatives

- List all of the general remedial options including the “no action” alternative;

- Screen out options which are not environmentally acceptable and those not technically feasible. The reasons for screening out options must be documented;
- List all the sub-options of the remaining general options;
- Screen out sub-options which are not acceptable for the same reasons as above.

Step III: Selecting the Preferred Alternative

There are a number of methods which can be used to select the preferred alternative from the list of sub-options developed in Phase II [76],[77],[78],[79]:

- Weighted scoring system
- Cost/benefit analysis
- Consensus of stakeholders
- Open or closed bidding (competitive bid)
- Treatability competition (choose technology which meets criteria at lowest cost).

In all cases the decision-making process should be documented in writing. Lastly, it should be noted that, for projects for which public consultation is required, the comments of the public need to be incorporated into the decision-making process. Meetings with the public, early in the decision-making process, are preferred because the public is then allowed to be involved in the process instead of being informed after decisions have been made.

The present work introduces the development of a three-step decision support system for helping management decisions of contaminated sites. The first section of the system (Figure 46) aims to the evaluation of risks associated to each site, in order to identify the most problematic cases. Based on previous models, the first risk assessment procedure intends to identify and classify sites suspected of contamination, based primarily on the activity that has taken place in the site, its associated material danger, and the local conditions as well as the historical background of the site that may be collected. A second risk evaluation step, based on the Baden-Württemberg (B-W) evaluation process, is performed to determine more accurately the management process that should be addressed for each site suspected of contamination. The B-W process contemplates five different site classes, each of them suggesting an appropriate kind of measures to be taken. The third step of the system is intended to suggest the most appropriate technology for the management of the contaminated sites determined in the two previous evaluation steps. Based on the B-W evaluation suggestions, both containment and remediation technologies for soil and groundwater are evaluated taken into account legal, technical, environmental, social and economical indicators. The assessment follows a logical framework approach to determine an optimized technology that can fulfill the required risk impairment at the site. Moreover, the points of view from all groups of entities participating as project stakeholders (site owners, project investors, municipalities, community) are taken into account in the decision, in order to provide with a more integral decision-support tool. In order to achieve the proposed goals, the project will consist on three main activities, Knowledge acquisition, Modelling and validation, and Development of the user interface.

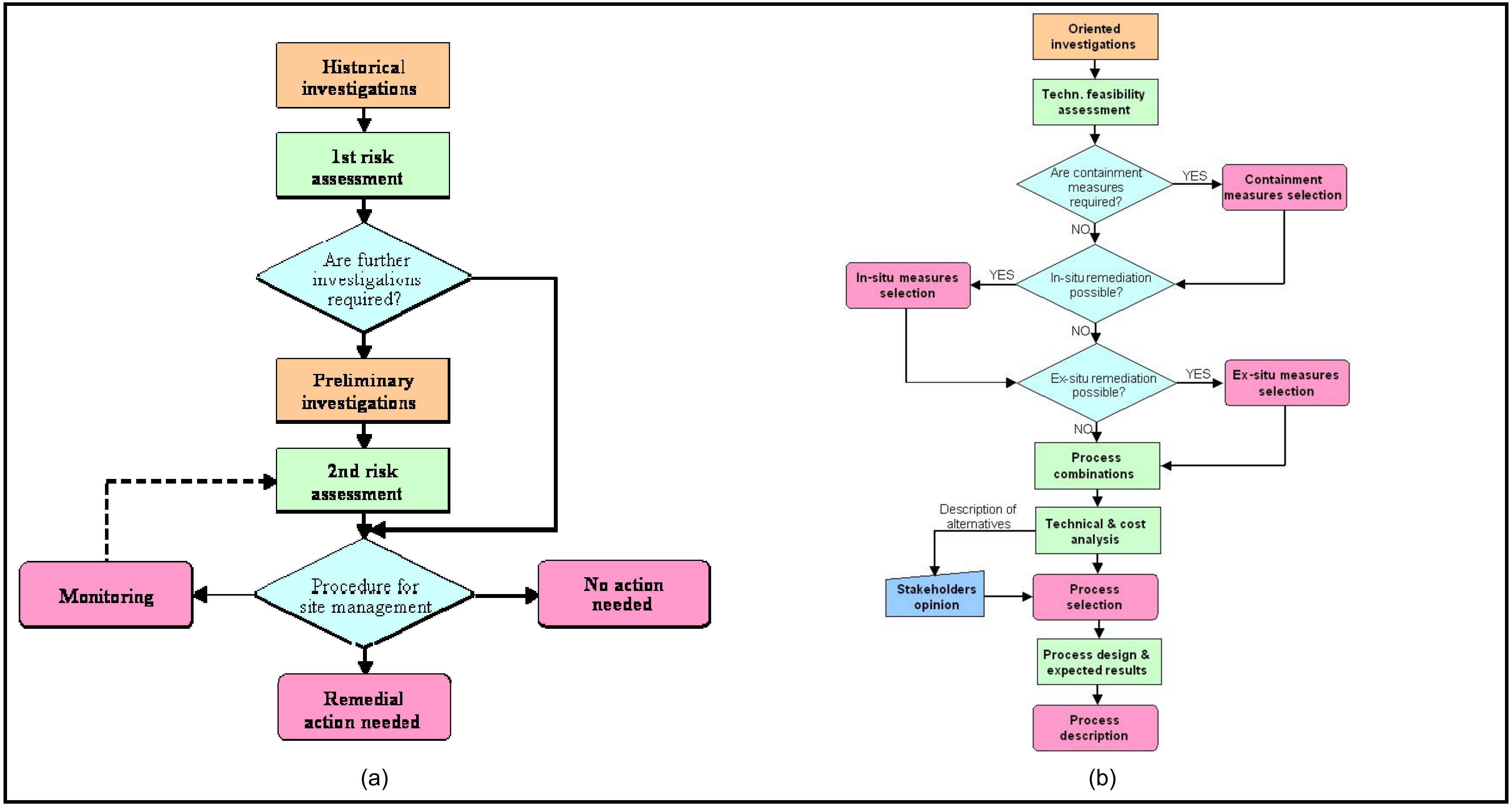


Figure 46. Flow diagram for the proposed risk assessment for suspected contaminated sites (a), and for the remedial action selection process (b).

3.2 Part I: Development of the risk management procedure

Risk management has been considered in the decision support system as a tool for establishing the priorities for management of (suspected) contaminated sites. Since the system is meant for authorities and stakeholders to utilize as a criterion for a large number and variety of sites, the risk assessment evaluation has been thought to first identify sites that are actually suspicious of contamination and/or posing an endangerment to the surrounding environment among the many industrial zones of a certain region. A second, more detailed risk assessment of the suspicious sites can provide with a classification of the studied areas, determining a suggested procedure for each case, which can range from performing immediate remediation measures to the registration of the site as harmless for the environment and the human health. The following sections introduce the developed risk assessment procedure for the classification of (suspected) contaminated sites.

3.2.1 First level risk assessment

The preliminary risk assessment procedure corresponds to an evaluation according to historical data collection concerning soil use and/or industrial activity. Based on previous models, this preliminary risk assessment procedure to identify and classify sites suspected of contamination, based primarily on the activity that has taken place in the site, its associated material danger, and the local conditions as well as the historical background information of the site that may be collected.

For this first evaluation, the main parameters considered are the ones that may be obtained through the collection of historical and geographical data, without the need of performing actual preliminary investigations on the site. The selected parameters can be organized as follows: (a) History of industrial activities performed at the site, (b) Extension of the suspicious area, and (c) Geographical, geological and hydro-geological conditions of the site.

The risk assessment procedure is based on previous risk assessment models, combining risk estimation approaches in a simplified way. The evaluation considers the associated risk to the material inventory of each industrial activity [178],[179] and a simplification of the EVAPASSOLD model [59],[60],[62] has been introduced to determine the influence of the site conditions into the risk evaluation. The defined risk assessment procedure has the form presented in eq. (4):

$$R = S_0 \cdot f(P) \cdot f(Extension) \cdot f(Env.Goods) \quad (4)$$

where:

S_0 : Corresponds to the associated endangerment value (S-Value) posed by the substances found in the evaluated old deposit/industrial site. This value has been derived from the Baden-Württemberg evaluation process [178], and it has a range value of 0 to 10 (see chapters 2.3.2 and 3.2.2.1).

Quantity	Class of groundwater endangerment	Probability of occurrence		
		Small	Medium	High
Little	Medium (2)	Construction & Cargo companies, hospitals, hotels, fuel traders, laundry shops, food enterprises, machinery dealers, textile processing companies.	Paint shops	
Little	Strong (3)	Joinery, Automobil trade, wood retails	Auto garages, locksmith's shops, apparatus & tools producers	Electric installations, wood/lumber preparation, laboratories
Medium	Medium (2)	Other big production enterprises	Disposal companies	Self-service petrol stations, mineral oil traders, print shops
Medium	Strong (3)		Small chemical traders, plastics processing, agricultural traders	Machine construction, fine mechanic, metal foundries, lead solders
Large	Medium (2)		Oil and grease producers	Petrol stations, paint producers
Large	Strong (3)			Chemical plants, chemical laundries, large metal processing companies, Pesticides production

Legend	
Priority 1	Suspected of high dangerousness
Priority 2	Suspected of moderate dangerousness
Priority 3	Suspected of low dangerousness. More information is needed
Priority 4	Suspected of harmless

Figure 47. Simplified criteria for establishing priorities and hierarchies of industrial and commercial sites, in terms of their endangerment to groundwater [181].

f(P) : Probability of occurrence for the endangerment of environmental goods, according to the evaluation suggested by Gläßner [181], and seen in Figure 47 (page 73). For this indicator, the function in eq. (5) has been derived.

$$f(P) = \begin{cases} 0.9 & \text{if Probability} = \text{Low} \\ 1.0 & \text{if Probability} = \text{Medium} \\ 1.1 & \text{if Probability} = \text{High} \end{cases} \quad (5)$$

f(Extension) : Indicator of the site's extension in terms of quantified characteristics as "Small", "Medium", and "Large". For this evaluation the sites are classified as "Small" when the extension is no larger than 1 ha, and classified as "Large" when the extension is larger than 5 ha [180]. For this indicator, the function defined by eq.(6) has been derived.

$$f(Extension) = \begin{cases} 1 & \text{if Extension} = \text{Small} \\ 1.1 & \text{if Extension} = \text{Medium} \\ 1.2 & \text{if Extension} = \text{Large} \end{cases} \tag{6}$$

f(Env.Goods): Function of the relevance of the environmental goods for the propagation of the contamination. As it may be observed in eq.(7), it is composed of *f(S)* and *f(G)* (i.e., functions of the influence of Soil and Groundwater, which are derived from the EVAPASSOLD model) and *f(N)*, which is defined as the function of the number of impacted environmental goods.

$$f(Env.Goods) = 1 + \frac{f(S) + f(G) + f(N) - 3}{10} \tag{7}$$

The remediation urgency of a suspected area depends in particular on the fixed protection goals and the local value attached to each individual endangered environmental good. With the evaluation of a single path and/or all endangerment paths, the investigation urgency of the contaminated areas can be certainly determined. The scores resulting from the individual evaluation sections are averaged, and the site is ranked into one of four hazard potential classes, denominated Priorities, of the hierarchy shown in Table 13 and Figure 47, being Priority 1 the most urgent one [181],[178],[179].

Table 13. Hierarchy description of evaluation process for suspected contaminated sites.

Priority	Points range	Denomination
1	8 – 10	maximum dangerousness
2	6 – 8	highly dangerous
3	4 – 6	low dangerousness
4	0 – 4	harmless

Because of time and economic restrains, and to avoid unnecessary field investigations, it is suggested to perform the second risk assessment procedure to all areas classified under the first two priority classes. Areas classified as Priority 3 should be further monitored and evaluated as well, but without urgent demand. Sites classified under Priority 4 are suggested to be regarded as harmless and simply registered in the database [182].

The evaluation considers the associated risk to the material inventory of each industrial activity (which will be fully explained in the B-W evaluation, chapter 3.2.2.1) and a simplification of the EVAPASSOLD model has been introduced to determine the influence of the site conditions on the risk evaluation. For the calculation of the parameters S_0, *f(S)*, *f(G)*, and *f(N)* the following sections are introduced.

a) Evaluation of the material danger of a site suspicious of contamination

The estimation of the pollutant danger is the starting point for the evaluation of suspected contaminated sites. If several pollutants and/or groups of pollutants are found, then the endangerment estimation is usually made with the highest S-value. For the determination of the material danger for old deposits, both volume and the deposited waste types are considered.

Endangerment class according to material inventory and industrial activity.

The material dangerousness of pollutants in the location is evaluated according to toxicological aspects. The considered pollutants can be present in form of individual or groups of chemicals. During sites evaluations, one must first examine which information about their material composition is available. If the spilled or deposited material is known in terms of the substances that were used, then it is possible to use the S-Value of the individual substance that has the highest priority (Table 14). If not, Table 15 can be used for an average value of endangerment class according to the field of industrial activity, as well as its associated probability of occurrence.

Table 14. Examples of S-Values according to the B-W evaluation process [183],[179].

Substance	S-Value	Substance	S-Value
BTEX	6.0	Cyanide	5.8
Phenol	4.8	Mercury, organic	5.5
PAH	5.0	PCP	6.0

Table 15. S-Values and probability of occurrence according to the industrial activity [178].

Industrial activity	Associated Danger Class (S-Value)	Probability of occurrence (1)
Agricultural Traders	4	2
Apparatus & Tools Producers	3	2
Auto Garages	3	2
Automobil Trade	3	1
Chemical Laundries	6	3
Chemical Plants	5	2
Construction & Cargo Companies	4	1
Fine Mechanic	4	3
Food Enterprises	5	1
Fuel Traders	4	1
Laboratories	6	3
Large Metal Processing Companies	5	3
Machine Construction	4	3
Metal Foundries	5	3
Mineral Oil Traders	5	2
Oil and Grease producers	5	2
Other Big Production Enterprises	5	1
Paint Producers	5	3
Paint Shops	5	2
Petrol Stations	5	3
Plastics Processing	5	2
Print Shops	5	3
Pesticides Production	6	3
Small Chemical Traders	4	2
Textiles Processing Companies	5	1
Wood Retails	4	1

(1) The values hereby presented show a function of the probability, determined by the following key: Low = 1, Medium = 2, and High = 3.

Material danger for deposits according to the volume and types of waste

The evaluation of the material characteristic is based on information about the existing dump volume and deposited waste material [179]. From the deposited waste composition, a risk value can be derived for each old landfill. These S-values serve as measure for the material danger in a deposit (Table 16).

Table 16. Material danger for deposits according to waste types and volume class (S-value)

Volume (m^3)	Material characteristic (waste type)			
	Ground excavation/ construction	Household and alike commercial	Landfillable special wastes	Not landfillable special wastes
1 – 1,000	0.5	1.0	3.0	5.0
1,001 – 10,000	1.5	2.5	4.0	6.5
10,001 – 100,000	2.5	4.0	6.0	8.0
100,001 – 1,000,000	3.5	5.5	8.0	9.0
> 1,000,000	5.0	7.0	9.0	10.0

b) Relevance of environmental goods for the propagation of contamination

The calculus of the parameters f(G), f(S) and f(N) are detailed as follows [60],[182].

Table 17. Evaluation of the parameter f(G) – risk of contamination effects on groundwater.

f(G)	Parameters for the evaluation of f(G) for groundwater
1	No utilisation possibilities for groundwater
1.3	Within influence area of water well
1.5	Run-off water, pore groundwater... sufficient only for individual and/or local water supplies.
1.7	Inside a (potential) area of regional and/or national drinking water supply
1.8	All declared sanctuaries and protected areas
2	In area of influence of an actual drinking water supply

Table 18. Evaluation of the parameter f(S) – risk of contamination effects on soil.

f(S)	Parameters for the evaluation of f(S) for soil
1	No possible use of surface.
1.2	Agricultural utilisation of surface possible.
1.5	Agricultural utilisation of surface or situation within natural reserve.
1.7	In urban areas without possibility of direct contact to children.
2	Usage of area and/or usage of direct surrounding as leisure area (also children‘s playground).

Table 19. Evaluation of the parameter f(N) – number of impacted or endangered environmental goods.

Number of impacted or endangered environmental goods	f(N)
1	1
2	1.3
3	1.7
4	2

3.2.2 Second level risk assessment

The second level of risk assessment consists on a simplification of the Baden-Württemberg evaluation procedure [178], as presented and proposed by Park [179]. The determination of the evaluation score takes place first separately according to the respective load paths and through the five evaluation steps:

- material danger (S-Value),
- location characteristics (V-Value),
- toxicological risk evaluation (H-Value), and
- land use characteristics (N-Value).

For the determination of the scores for all evaluation steps, the German legislation (German Waste management law [193], German Law for the protection of air [194] and German Law for the protection of soil [211]) ha sbeen used as evaluation standards. The overall evaluation score results as the average of the individual points from the five evaluation steps (which range between 0 to 10). If several environmental goods are evaluated for an individual site, each evaluation is performed individually.

3.2.2.1 Evaluation of the danger caused by substances (S-Value)

The same procedure is used as in chapter 3.2.1, First level risk assessment, see page 72.

3.2.2.1.1 Material danger for deposits according to the volume and types of waste

The same procedure is used as in chapter 3.2.1, First level risk assessment, see page 72. For the estimation of the hazard potential of the deposited wastes refer to Table 16.

3.2.2.1.2 Endangerment class according to material inventory and industrial activity.

The material dangerousness of pollutants in the location is evaluated according to toxicological aspects. The considered pollutants can be present in form of individual or groups of chemicals, as shown in Table 14. If the existing materials at the site are known, the evaluation is performed according to the material inventory and surface size, with the values presented in [178],[179] and Table 20. If the characteristics of the materials at the site are unknown, then the industry key directory introduced by [178],[179] may be used. With this value, and considering the size of the site, the S-Value can be obtained through Table 20.

Table 20. Endangerment class (S-value) for locations according to material inventory and industrial activity, depending on site surface.

Endan-germent class [a]	Site surface (m²)						
	1 – 10	11 – 100	101 – 1,000	1,001 – 5,000	5,001 – 10,000	10,001 – 100,000	> 100,000
1	0.1	0.3	0.5	1.0	1.5	2.0	2.5
2	0.5	1.0	1.5	2.0	3.0	3.5	4.0
3	1.5	2.0	3.0	3.5	4.0	5.0	6.0
4	2.5	3.0	4.0	5.0	6.0	7.0	7.5
5	3.0	4.0	5.0	6.0	7.0	8.0	9.0
6	4.0	5.0	6.0	7.0	8.0	9.0	10.0

a) Endangerment class according to material inventory and industrial activity can be found in [178],[179].

3.2.2.2 Determination of site-specific local conditions (V-value)

After determining the material danger, the next step is to determine the local conditions at the site. In this step takes place the evaluation of the geological and hydrogeological characteristics of the location and its surroundings. The possibility of pollutant transport depends on the permeability, support effect and the porosity of the soil. Besides, the pH value has substantial influence on possible mobilization processes [178]. The conditions of the deposited materials at the site and its surroundings are measured and evaluated.

3.2.2.2.1 Determination of the endangerment class as a function of the formation of new seeping water.

The resulting quantities of seeping water in contaminated surfaces are primarily determined by the local conditions (e.g. annual precipitation, compression degree, age and the quality of the site's recultivation). The water balance of a site is schematically represented by the box model in Figure 48. Considering this simplified box model, the water balance can be represented as in eq. (8):

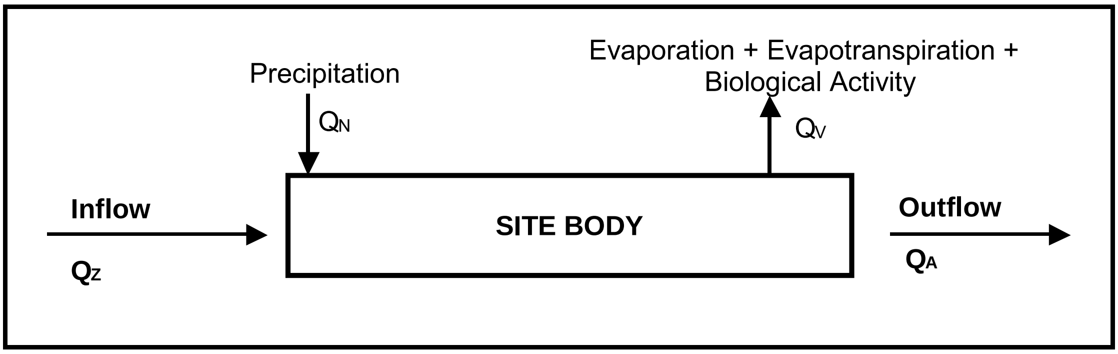


Figure 48. Simplified box model for the water balance in a semi closed site [184]

$$Q_Z + Q_N = Q_A + Q_V \quad (8)$$

Normal values for Q_V range from 0 to 50%, being the latter a most commonly used one for climatic conditions in Austria [24],[25],[184]. Table 21 presents the suggested values for the endangerment class of a site according to the formation of new seeping water.

Table 21. Endangerment class as a function of the formation of new seeping water.

New seeping water formation [mm/a]	Endangerment class
> 700	9
700 – 600	8
600 – 500	7
500 – 400	5
400 – 300	3
300 - 200	2
200 – 100	1
< 100	0.5

3.2.2.2.2 Determination of the endangerment class as function of the permeability

The Darcy's law permeability factor (k_f, [m/s]) is predominantly applied to the gas and liquids flow through soil. Soil porosity makes a flow possible towards a potential gradient. The k_f-value varies from one soil type to another between 10^{-3} and 10^{-9} m/s, where sand soils always exhibit relatively high values, while for loams and clay soils it can be considered as a function of the aggregation degree (Table 22). For the determination of the endangerment class as a function of the soil permeability, the values presented in Table 23 are used.

Table 22. Hydrogeological parameters of different soil types [185],[186].

Soil type	Particle size [mm]	k_f [m/s]
Gravel	> 2.0	$1.2 \cdot 10^{-3}$
Coarse sand	0.6 - 2.0	$1.2 \cdot 10^{-4}$ - $1.2 \cdot 10^{-3}$
Middle sand	0.2 - 0.6	$5.8 \cdot 10^{-5}$ – $1.2 \cdot 10^{-4}$
Fine sand	0.06 - 0.2	$3.0 \cdot 10^{-6}$ - $5.8 \cdot 10^{-5}$
Silt	0.002-0.06	10^{-9} – $3.0 \cdot 10^{-6}$
Clay	<0.002	10^{-9} – $3.0 \cdot 10^{-6}$
Peat	-	10^{-9} – $3.0 \cdot 10^{-6}$

Table 23. Determination of the endangerment class as a function of the permeability factor.

Permeability factor (k_f) [m/s]	Endangerment class
> 10^{-4}	9
10^{-4} - 10^{-5}	8
10^{-5} - 10^{-6}	7
10^{-6} - 10^{-7}	5
10^{-7} - 10^{-8}	3
10^{-8} - 10^{-9}	2
< 10^{-9}	0.5

3.2.2.2.3 Determination of the endangerment class as a function of the number of missing protection facilities.

In the past, wastes were usually deposited without previous planning, without today's necessary safety devices, without effective control and without documentation. In such deposits without basis sealing (bottom liner) and frequently installed on permeable underground (even partly within the groundwater range), leachates can easily permeate into the surrounding rocks and into the groundwater. Among the available protection facilities for preventing gas and seeping water emissions in old deposits, the following can be numbered:

- Base sealing (bottom liner)
- Intermediate layers
- Drainage system
- Seeping water collecting system
- Surface cover
- Defense wall
- Gas collecting system
- Soil recultivation

Table 24 presents the relationship between the endangerment class and the number of missing protection facilities in a suspected contaminated site. In the case of having a site with all the protection facilities, the endangerment class is considered zero (0, harmless).

Table 24. Determination of the endangerment class as a function of the number of missing protection facilities.

Number of missing protection facilities	Endangerment class
< 2	1
2	3
3	4
4	6
5	7
6	8
7	9
> 7	10

3.2.2.2.4 Influence of the pH values and sorption coefficient of the pollutants on the endangerment degrees.

In waste deposits, the acid fermentation phase is characterized by the formation of low fatty acids, which are discharged mainly with the formed leachates. The organic load in these can then achieve high concentrations. Moreover, a sinking of the pH value is produced, and accordingly the solubility of heavy metals (e.g. Cd, Zn, Cu, Pb) is enhanced.

Absorption can be defined as a process in which atoms, ions or molecules of a substance enter a bulk phase. If absorption is a physical process not accompanied by any other physical or chemical process, it usually follows the Nernst partition law, eq.(10) [188]. In this case, the partition coefficient (K_d) is defined as the ratio between the concentration at the solid phase (bulk phase; C_F) and the concentration in the liquid (solute, C_w). The sorption coefficient (K_{OC}), referred to the organic carbon content (Corg), results as:

$K_d = C_F/C_W$ (9)

$K_{OC} = K_d * 100/Corg. (\%)$ (10)

K_{oc} values can therefore vary for the different chemicals, ranging from values of <50 (e.g. Benzol), to 50,000 (for some PAHs). For the determination of the influence of the sorption coefficient of the pollutants and the pH value on the endangerment class, the values of Table 25 are introduced.

Table 25. Influence of the sorption coefficient of the pollutants and the pH value on the endangerment class.

Sorption coefficient (K_{oc})	Endangerment class as function of pH value		
	pH < 5	5 < pH < 9	pH > 9
Low (< 10^2)	9	7	5
Medium ($10^2 < K_{oc} < 10^3$)	7	5	3
High (>10^3)	5	3	1

3.2.2.2.5 Influence of the pH values and the redox potential of soil on the endangerment degree

The affinity of substances in the soil solution for electrons can be measured by its redox potential (E_h). The more strongly reducing is a substance the less is its affinity for electrons so the lower is the potential. The oxidation - reduction (redox) potential of the soil is a measure of the tendency of the soil solution to accept or donate electrons. Oxidation involves a loss of electrons, reduction results in a gain. The more strongly oxidizing a solution, the higher its potential; the more reducing, the lower. In a well-aerated soil, oxygen serves as the electron acceptor and the potential is high. As O_2 is depleted, the potential drops and other components serve as electron acceptors depending on their tendency to accept or donate electrons. In the soil, the major components involved are nitrate ions, manganese, iron compounds, sulfate, and eventually CO_2 [190].

The redox potential of the soil influences the metals binding and thus their mobility. An oxygen-rich and well-ventilated soil possesses generally a high redox potential of over +400 mV. Poor oxygenated soils have low to negative redox potentials. With negative redox potentials (0 to -200mV), many metals form low soluble sulfide complexes. Sulfide-containing soils are able to firmly bind metals [187],[189]. The solubility of metals is high at low pH-values both in aerobic and in anaerobic process conditions. However, the solubility of iron is highest in anaerobic process conditions while the solubility of cadmium is highest in aerobic process case. Figure 49 shows the solubility of iron, manganese, cadmium and mercury, versus redox potential and pH-value. In the aerobic case is iron precipitated as ferric hydroxide, while cadmium in the anaerobic case is precipitated as cadmium sulphide. In the anaerobic case is corrosion of the metal controlled by protective properties of metal sulphide precipitations on the metal surface. The corrosion mechanisms of iron in soil [192] may be used as an example. The corrosion in aerobic soil is stifled by the deposition of iron(III) oxide-hydroxide. During anaerobic conditions sulphate reducing bacteria produce hydrogen sulphide. the organic material is decomposed by sulphate and nitrate reducing bacterias. If the hydrogen sulphide concentration is larger than the ferrous ion concentration, the corrosion of iron may in this phase be stifled by deposition of ferrous sulphide. The ferrous ions in soil orginates from leaching of inorganic soil particles by humic acids [190].

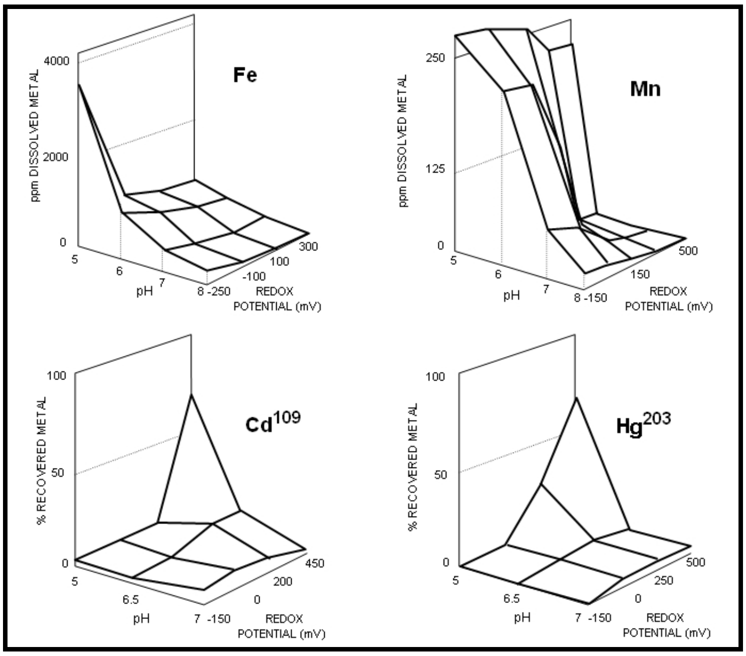


Figure 49. Solubility of iron, manganese, cadmium and mercury, versus redox potential and pH-value [191].

For the determination of the influence of the redox potential of the pollutants and the pH value on the endangerment class the values of Table 26 are introduced into the evaluation.

Table 26. Influence of the pH value and the redox potential on the endangerment class.

Redox potential [mV]	Endangerment class as function of pH value		
	pH < 5	5 < pH < 9	pH > 9
> +50	9	7	5
-50 < E° < +50	7	5	3
< -50	5	3	1

3.2.2.2.6 Determination of the endangerment class as a function of the humus content and the pH value of soil

Humic substances favour the formation of porous structures with high water capacities, working as a storage for exchangeable-bounded nutrients and pollutants. The cation exchange capacity of the humic substances is strongly pH dependent [195]. For the determination of the influence of the humus content of soil and the pH value on the endangerment class, Table 27 presents the suggested values for this evaluation.

Table 27. Influence of the pH value and the humus content on the endangerment class.

Humus content [%]	Endangerment class as function of pH value		
	pH < 5	5 < pH < 9	pH > 9
0 – 5	9	8	6
5 – 10	7	6	4
10 – 20	5	4	3
20 – 30	4	3	2
> 30	3	2	1

3.2.2.2.7 Determination of the endangerment class as a function of the clay content and pH value of soil

Clay minerals play an important role in soils' nutrient sorption and ion exchange processes. Clay minerals and humic substances are binded under suitable conditions to form clay-humus complexes. For the determination of the influence of the clay content of soil and the pH value on the endangerment class, refer to Table 28.

Table 28. Influence of the pH value and the clay content on the endangerment class.

Clay content [%]	Endangerment class as function of pH value		
	pH < 5	5 < pH < 9	pH > 9
0 – 10	9	8	6
10 – 20	7	6	4
20 – 30	5	4	3
30 – 40	4	3	2
> 40	3	2	1

3.2.2.2.8 Determination of the endangerment class as a function of the cation exchange capacity of soil

The cation exchange capacity (CEC) of soils is determined by their type and content of clay minerals and humus, and the pH value. If the pH value of acid soils is increased, so does the CEC and thus the quantity of exchangeable cations [189]. For the determination of the influence of the CEC in soil and the pH value on the endangerment class, the values of Table 29 are introduced.

Table 29. Influence of the pH value and the CEC on the endangerment class.

CEC [$mmol_c$/kg]	Endangerment class as function of pH value		
	pH < 5	5 < pH < 9	pH > 9
0 – 100	9	8	6
100 – 200	7	6	4
200 – 300	5	4	3
300 – 400	4	3	2
> 400	3	2	1

3.2.2.3 Evaluation of the toxicological risk (H-Value)

An important aspect of risk evaluation is the determination of the actual harmful effects of the materials that are supposed to pose a danger to the human health. To this subject also belongs the determination of the relationships between the concentration of the pollutants and their effects. Such effects cover acute toxicity, chronic toxicity, mutagenicity and carcinogenic properties. For the evaluation of a material, its acute and chronic toxicity, as well as its carcinogenic and mutagenic properties are assessed in a method developed by the Institute for water-endangering substances at the Technical University of Berlin (Institut für wassergefährdende Stoffe – IWS) [183],[179]. Table 30 presents a summary of the evaluations for human-toxicological risk for some common pollutants. For a complete list, refer to [178],[179].

Table 30. Examples of human-toxicological risk evaluation [183],[179]

Rank N°	Substance	Value for acute toxicity	Value for chronic toxicity	Value for mutagenic properties	Value for carcinogenic properties	H-Value, substance dangerousness
1	Anthracene	1	1	7	7	5
29	Phenol	4	4	8.5	8	6.5
61	Benzol	4	4	10	10	7.6
74	Cyanide	10	7	8.5	7	8.2
86	Mercury, organic	10	10	9	7	9.1
89	PCP	10	10	8.8	9	9.5

3.2.2.4 Evaluation of the characteristic land use (N-Value)

The present or future land use within the range of a contaminated location is a substantial parameter for the evaluation of a redevelopment demand. Since very different uses are possible, different qualities for groundwater and soil in terms of pollution levels may result. The meaning of the groundwater depends on whether and in which kind a present or future use exists, which water quality necessary for it and which impairments of the uses are to be expected by the suspected site. If the groundwater is used as drinking water and the danger source lies in the water inflow range of the uptake point, the importance of this groundwater is particularly high. Hence, the distance from the contamination source to the area intended for development represents an important evaluation factor.

For the determination of the endangerment class as a function of the location of use, the values of Table 31 (page 85) are introduced. Further surcharges and reductions of the endangerment class are given, depending on present and future conditions.

Table 31. Determination of the endangerment class as a function of the location of use

Environmental good	Distance from protected property [m]					
	Inside	1 – 10	10 – 100	100 – 500	500 – 1000	> 1000
Environmental goods: Groundwater, surface waters, soil						
Drinking Water Acquisition	10	9	8	7	6	5
Special Drinking Water protected zone	9	8	7	6	5	4
Protected drinking water zone I	8	7	6	5	4	3
Protected drinking water zone II	7	6	5	4	3	2
Farming zone (with food production)	7	6	5	4	3	2
Children Recreation Places	7	6	5	4	3	2
Leisure & Recreational Places	6	5	4	3	2	1
Natural Protected Areas	6	5	4	3	2	1
Residential Area	6	5	4	3	2	1
Industrial Area	5	4	3	2	1	0.5
Environmental goods: Air						
Children Recreation Places	10	9	8	7	6	5
Leisure & Recreational Places	9	8	7	6	5	4
Natural Protected Areas	8	7	6	5	4	3
Residential Area	7	6	5	4	3	2
Farming zone (with food production)	6	5	4	3	2	1
Industrial Area	5	4	3	2	1	0.5

Further supplements/reductions:	Yes	No
Has an alternative supplying possibility been planned?	-2	+2
Will the groundwater or aquifer be used as drinking water in the future?	+2	-2
Is the contaminated site located in the flooding area?	+2	-2
Is the production of vegetable food intended in the future?	+2	-2
Are there protected animals present at the site?	+2	-2
Are the waters used for agricultural purposes?	+1	-1

3.2.2.5 Final evaluation of the site risk potential

The remediation urgency of a suspected area depends in particular on the fixed protection goals and the local value attached to each individual endangered environmental good. With the evaluation of a single path and/or all endangerment paths, the investigation urgency of the contaminated areas can be fairly determined. The scores resulting from the individual evaluation sections are averaged, and the site can then be ranked into one of the five hazard potential classes (i.e., A, B, C, D, E) of the hierarchy shown in section 2.3.2. Sites ranked as category case E are considered very critical and regarded with priority. In case of a site ranked with category case A, no further critical evaluation is accomplished.

Table 32. Hierarchy description of the Baden-Württenberg risk-based evaluation process for suspected contaminated sites.

Case	Points range	Actions	Denomination
A	0 – 2	Inscription in contaminated sites register	harmless
B	2 – 4	Routine monitoring	low dangerousness
C	4 – 6	Check thoroughly possibilities for a danger impairment	dangerous
D	6 – 8	Execution of containment for site securing	highly dangerous
E	8 – 10	Execution of immediate containment and remediation measures	maximum dangerousness

The following are the defined possible procedures to address after the completion of the site evaluation process:

- **Case E: Execution of immediate containment and remediation measures (for maximum dangerous classified sites)**

The evaluation result of the site points towards an immediate containment and remediation of the location. The necessary measures of containment and remediation must be accomplished through physical, chemical and/or biological processes (see chapter 2.4). Immediate measures can be accomplished for the danger impairment, and for the investigation and execution of the remediation/containment measures. For the remediation of a site, excavation and off-site disposal of the contaminated material may appear suitable and the obvious procedure. However, only the specific local situation of the site (contaminants present, geological, hydro-geological, social and economic conditions, etc.) will finally influence the selection of the necessary measures to be taken, as there is no general solution and each site has to be tackled individually.

- **Case D: Execution of containment (for highly dangerous classified sites)**

A case D evaluation result points to the (e.g. temporary) containment of the site. Immediate measures for danger impairment and the investigation, planning and execution of the (provisional) containment are necessary. In case of an endangerment potential from a (suspected) contaminated site through its actual use, such endangerment must be hindered by an appropriate security or containment measure.

- **Case C: Check thoroughly possibilities for a danger impairment (for dangerous classified sites)**

According to the result of the evaluation process, a direct danger for the environment is not expected at present and thus, remediation measures are not (immediately) necessary. Nevertheless, the deposited contaminated materials can lead to an increase of the hazard potential, due to sensitive use and unfavourable location conditions. In this case, a danger reduction (e.g., site containment measures) may be necessary, according to the evaluation of the past testing results. Danger reductions are feasible if they ensure sufficient security against the existing danger, and if remediation measures would provide no better success whilst requiring disproportionately higher expenditures. The further investigations must consider the load path, as well as the pollution parameters and the exact sampling points that must be examined.

- **Case B: Routine monitoring (for low dangerous classified sites)**

A class B classification of a suspected area points out that neither containment nor remediation actions are necessary, but that a location-specific routine monitoring is recommended. The regular monitoring has the goal to guarantee that eventual dangers for public security are recognized in time through recurring observations and investigations. This situation is in particular necessary if after the investigation and evaluation process there is sufficient evidence to state that a potential risk exists even without change of the land use.

- **Case A: Inscription in (suspected) contaminated sites register (for harmless classified sites)**

Locations that are assigned to this class exhibit only a very small hazard potential. However, since a further residual risk will always exist, these areas must be included in the (suspected) contaminated sites register. In case of changes in the use of these areas or their surrounding fields, a new site evaluation may be considered necessary.

3.3 Part II: Development of a selection procedure of feasible technological alternatives for site remediation

Goal of this section is to build up the structure for a selection procedure model that can deal with the identification of suitable technologies for the remediation of a contaminated site. In order to achieve this goal, a set of parameters have been defined to characterize the conditions of the site.

The model considers the hydrogeological characteristics of the site as well as the contamination present in the site (pollutants, affected environmental goods, extension of the contamination) and the risk class of the site from the first module. At the same time, the model considers several technological alternatives for site containment and remediation, which are then evaluated for their suitability for the problem at hand.

The following sections describe the steps to follow for building up the intended module for the selection of suitable technologies for site management.

3.3.1 Formulation of the decision module

The decision module has been structured upon the developed decision trees. It has been decided to utilize a mathematical tool called “fuzzy logic” for establishing the “reasoning” to be carried out when approaching the solution of the selection of suitable technologies to address the present contamination and conditions of a site.

Fuzzy Logic deals with those imprecise conditions about which a true/false value cannot be determined. Much of this has to do with the vagueness and ambiguity that can be found in everyday life. For this reason, fuzzy logic has been commonly referred to over the last decade for programming decision support systems that deal with a high level of uncertainty [201],[202].

Subjective responses are relative to an individual's experience and knowledge. Human beings are able to exert this higher level of abstraction during the thought process. For this reason, Fuzzy Logic has been compared to the human decision making process. Conventional Logic (and computing systems for that matter) are by nature related to the Boolean Conditions (true/false). What Fuzzy Logic attempts to encompass is that area where a partial truth can be established, that is a gradient within the true/false realm [201],[202]. Fuzzy logic has been used in several study fields, from medicine to the control theory in engineering, due to its capability to work under uncertainty [203],[204],[205],[206]. A list of general observations about fuzzy logic is given as follows [202],[206]:

- Fuzzy logic is conceptually easy to understand. The mathematical concepts behind fuzzy reasoning are very simple. What makes fuzzy nice is the “naturalness” of its approach and not its far-reaching complexity.
- Fuzzy logic is flexible. With any given system, it’s easy to lay more functionality on top of it without starting again from scratch.
- Fuzzy logic is tolerant of imprecise data. Everything is imprecise if you look closely enough, but more than that, most things are imprecise even on careful inspection. Fuzzy reasoning builds this understanding into the process rather than tacking it onto the end.
- Fuzzy logic can be built on top of the experience of experts. It lets to rely on the experience of people who already understand a complex system.
- Fuzzy logic is based on natural language. The basis for fuzzy logic is the basis for human communication. This observation underpins many of the previously mentioned statements.

For the construction of the technology selection module, the Fuzzy Logic Toolbox® of the Matlab® software [202] has been utilized. The developed tool does not intend to be programmed with fuzzy logic but to use the powerfulness of the Matlab toolbox to operate under this environment. The decision trees have been built under the fuzzy logic environment, in which simple “if-then” rules are applied to determine the most adequate answer in each step of the decision process. In order to develop the set of rules that will conform the selection procedure, a literature survey has been performed to determine the suitability of application of the various technological alternatives according to the pollutants present in the site, and the site conditions that are determinant for the impossibility of applying a certain remedial option.

The selection of a treatment technology for a specific site often depends on the physical and chemical properties of the contaminants at the site. For example, VOCs are amenable to treatment by certain technologies, such as soil vapor extraction (SVE), because of their volatility. In other cases, metals, which are not volatile and do not degrade, are not amenable to treatment by SVE, thermal desorption, or bioremediation. However, because metals form insoluble compounds when combined with appropriate additives, such as Portland cement, solidification/stabilization is most often used for treatment of those contaminants [81],[198]. The remediation targets to be considered during the planning phase are dependent on the type of redevelopement or afteruse of the remediated site. For that reason, the limit values for the different soil uses must be established for the evaluation process. The final step of the development procedure consists on formulating the membership functions of all parameters according to a logical point of view, i.e. providing a qualification scheme according to their actual numerical value. The final scheme of the decision trees and of the membership functions developed for all the parameters are shown in detail in chapter 4.2.

3.3.2 Technologies addressed in the technology selection model

For the application of the balanced scorecard for the selection of appropriate remedial options, a total of eight groups of technologies for the remediation and containment of groundwater and soil have been selected, being the most commonly applied technologies in contaminated sites management (Table 33).

Table 33. Groundwater and soil remediation technologies addressed in the evaluation

Technology class	Addressed technology
Soil remediation technologies	
1. Bioremediation	*(in-situ) bioventing (BVE)* *(in-situ) air sparging (SAS)* *(on-site & off-site) composting (COM)*
2. Physical and chemical remediation	*(in-situ) soil air extraction (SAE)* *(on-site & off-site) soil washing (SWA)*
3. Thermal treatment	*(off-site) Incineration (INC)* *(in-situ) Thermal desorption (TDE)*
4. Containment	*Solidification stabilization (SOL)* *Capping (CAP)*
5. Excavation, Separation (Triage) and Disposal [a]	*Excavated-soil landfill (BOD)* *Demolition-waste landfill (BAU)* *Residual-materials landfill (RES)* *Mass-waste landfill (MAS)*
Groundwater remediation technologies	
1. Active measures	*Pump & Treat + Bioremediation (PTB)* *Pump & Treat + Chemical Remediation (PTC)*
2. Passive measures	*Air sparging bioremediation (GAS)* *Reactive walls (RWA)*
3. Containment	*Sheet pile walls (UMS)* *Slurry trench walls (SLI)* *Thin cut-off walls (SMA)* *Vienna double wall chamber system (WDK)*
4. Removal of groundwater contaminants source	*See soil remediation technologies under 5. Excavation, Separation (Triage) and Disposal*

[a] Types of sanitary landfills defined according to Austrian legislation [223],[224].

As already mentioned, a benchmarking process has been conducted to determine the most important parameters of the selected technologies. By conducting this comparative evaluation it was possible to obtain a broad spectrum of the advantages and disadvantages of each selected technology when applied to certain site conditions [217],[144].

3.4 Part III: Evaluation of feasible alternatives and final selection of an appropriate remediation and/or containment technology

In remediation of contaminated sites, various types of problems occur at the same time and therefore numerous goals have to be achieved simultaneously. The evaluation process to identify the potential state-of-the art remediation technologies (as described in the previous section, chapter 3.3) resulted in a bundle of possible technologies likely to be used. A further and more detailed analysis of the defined possible technologies requires a complex and multidimensional evaluation of those selected technologies as well as the characteristics of the site and its environment in order to decide on the final remediation technology to be applied. To establish such a complex analysis, Logical Framework Approach (LFA), an analytical and management tool has been applied to reach an agreement on the problems, deduced goals, required strategies of appropriate technologies and related activities.

LFA consists of two parts, the analysis and planning phases. The first phase includes the complex analysis and establishment of a relevant group of possible involved stakeholders and decision-makers in the field of contaminated sites remediation. Morover the analysis phase deals with the formulation and structuring of all process-related problems and their reformulations into a hierarchical objective tree.

The planning phase of the LFA includes the identification and evaluation of relevant indicators, deriving them directly from the bottom (measurable) goals. These indicators quantitatively describe the appropriateness level of the possible technologies according to the characteristics of the contaminated site in terms of technical, social, economic and environmental aspects.

Stakeholders have diverse preferences and goal-achievements expectations, and thus the application of their various quantitative indicator-sets, as well as their numerically expressed preferences of goals, results in different remediation technologies to be proposed. The evaluation of the technologies through the BSC therefore proceeds with a multidisciplinary context to achieve an overall inclusion of the perspectives of all decision-makers in remediation projects of contaminated sites and the various contaminated site characteristics for the evaluation of the possible technologies for site management (which are identified in the previous step of the knowledge-based model).

Considering all of the above, the BSC results in a decision support tool for selecting the most suitable technology for the remediation of contaminated soil and groundwater, taking into account all aspects and components affecting or influenced by the contaminated site. After presenting the formulation of the BSC, this chapter introduces a risk analysis procedure for the evaluation of the operational behavior of the selected technology under several possible scenarios. This evaluation considers the probability of occurrence and consequences of an unexpected event during and after the restoration measures. Although this procedure must be established in each individual study case, as it deals with the specific current and future conditions of the contaminated site in study, this section aims to exemplify some general aspects against which the selected technology shall be evaluated in order to determine its appropriateness and to ensure the acceptance of the community as well as of the stakeholders involved in the project.

3.4.1 Formulation of the Balanced Scorecard (BSC)

Through modifying the original LFA, the **analysis phase** has been conducted by performing stakeholders-, problem- and objectives analysis [212] and measurable **indicators** have been selected and characterized by their identification, description, calculation, and determination of their weighting parameters.

3.4.1.1 Analysis phase

The analysis phase contains the multi-dimensional goals definition that shall be considered as the reformulation of the problems; as main goal the selection of an appropriate technology for the management of a contaminated site is drawn up.

Structuring the goal tree

For accomplishing the analysis phase, the initial study was focused on the determination, description and integration of the most concerned parties of a remediation project, such as organizations or individuals (stakeholders), into the decision process. Such study is aiming to identify the most important points of view of the different stakeholders and their prioirities when it comes to take a decision in a remedial project. In this regard, the aspects to be considered and evaluated by the stakeholders have been categorized into four different dimensions: social, economic, environmental and technical.

Following the identification and involvement of the stakeholders, the main goal of the remediation process was structured into sub-goals by grouping them according to the above mentioned four dimensions. The goals are thus broken down into sub-goals, whose hierarchy results into an objective tree for contaminated sites remedial projects.

Weighting of goals

For a general alternative (A_i), both utility function ($U(A_i)$) and weight (w_i) of an indicator can. be defined through a simple linear composition rule, as presented in eq.(11) [215].

$$U(A_i) = \sum_{j=1}^{m} w_j \cdot u_j \cdot (c_j(A_i)) \tag{11}$$

where c_j = $(c_1, \dots, c_m)$ the set of attributes,
u_j = $(u_1, \dots, u_m)$ set of utility functions,

$A_i =$ $(A_1, \ldots, A_n)$ the set of alternatives.

$w_j =$ $(w_1, \ldots, w_m)$ the set of weights (relative importance), with $\sum_{j=1}^{m} w_j = 1$

Utility functions were defined for each indicator to assign single preference value for each of their alternatives. By applying predefined weights and algorithms, utility values can be calculated to characterize each of the remediation options. The maximum obtained utility value should determine the most beneficial remediation option in a certain decision system [216]. In this work, the types of utility functions that have been utilized range from single values coming from a benchmarking process of remedial technologies [144],[217], to continuous and discrete functions [212],[216].

As weighting methods, the simple multiattribute rating technique (SMART) and the analytic hierarchy process (AHP) procedures have been implemented in this work [162]:

- **SMART – Simple multiattribute rating technique:** In the SMART rating technique, the decision maker is asked to determine an attribute that has the least importance for the goal to be achieved. This attribute is given the value of 10 points. For all other attributes, the decision maker is asked to provide with an importance value greater or equal to 10 points, referring to the least important one. After the comparisons the points are normalized and the weight of the attribute i is calculated as defined in :

$$w_i = \frac{p_i}{\sum_{j=1}^{n} p_j} \tag{12}$$

  where p_i corresponds to the points given to the attribute (objective) i, and n is the total number of the attributes (subobjectives).

- **Analytic Hierarchy Process (AHP):** AHP is based on paired comparisons and the use of ratio scales in preference judgements. In the standard form, alternatives are not differentiated from the attributes and objectives but are treated as a bottom level of the hierarchy. The decision maker is asked to give the ratio of weights for the addressed attributes (i.e., objectives, alternatives), r_{ij}, as defined in eq.(13).

$$r_{ij} = \frac{w_i}{w_j} \tag{13}$$

At this point, the main goal of the remediation of contaminated sites has been broken down into sub-goals until the level where these lower sub-goals (bottom goals) can be measured with the introduction of indicators, which have been defined, described and "calibrated". The quantification of the relative importance of the goals results in weights so the complex system is defined, having a certain level of sensitivity. This level of sensitivity must be determined with a sensitivity analysis, which is described in the following section.

3.4.1.2 Planning phase

The structuring of the objective tree has to be done until its components achieve a measurable level, the level of **indicators**. According to their definition from Chapter 2.6.3, the indicators allow the simplification of measuring the achievement of all sub-goals, goals and main goal by providing quantitative information regarding the characteristics of the goals to be evaluated. In this work, all indicators have been directly 'top-down' derived from the objectives tree by breaking it down. From Table 34 it is also possible to identify the most important aspects for the definition of the indicators. After defining the measurable indicators, it is necessary to determine their utility functions (either continuous or discrete) to transform them into numerical scores (e.g. from 0 to 10) and thus to measure their value. The second step is the application of weighting methods for establishing the measured differences between the relative importances of the evaluated goals and applies them in the balanced scorecard structure [213]. By including these two steps in the developed objective tree it is possible to establish a consolidated balanced scorecard.

Table 34. Required parameters for the definition of the selected indicators.

Characteristic	Required parameters
Identification	ID (Identity code) Indicator long name Indicator short name
Description	Units Description of units Supported Sub-goal Provider (responsible of the information) Relevance/Purpose of the indicator Art of the indicator Temporal/spatial level Relationship to other indicators/goals
Calculation	Value of indicator Description of calculation Value to be achieved Limitations
Calibration	Minimum value of indicator Maximum value of indicator Minimum Score of indicator Maximum Score of indicator K.O. Criteria Utility function
Weight	Indicator absolute weight Indicator relative weight
Other	References

3.4.1.3 Sensitivity analysis of the technology selection model

Uncertainty in a model can have different origins in different decision problems. It may be due to either incomplete information or fluctuations inherent in the problem or unpredictable changes in the future. A model can be affected by changes in either parameters or drivers (exogenous variables) [162]. In order to tackle uncertainties it is proposed to perform a "sensitivity analysis", whose goal is the evaluation of the system under a series of uncertainties at the highest levels of the assessment process. An understanding of the influence of the above on the course of action suggested by the model is crucial because different levels of acceptance (by the general public, by the decision-makers, by stakeholders) may be attached to different types of uncertainty [162].

In the problem at hand, there are two types of uncertainties that have been considered to have the highest impact on the obtained results. These uncertainties are first the *effect of the hierarchy* of the attributes on the developed model, and second the *reference point effect*, dealing with the analysis of the situation in which the decision maker made his preferences.

- **The effect of hierarchy:** The form of the objectives hierarchy is likely to affect the attribute weights. As previously mentioned, different methods of weighting are likely to result in different hierarchies. Specifically, there is evidence suggesting that the top-down approach yields steeper value trees with more layers between the top and bottom level [218]. Moreover, hierarchical weighting leads to higher weight ratios when compared with non-hierarchical weighting [214]. That is, weight ratios in non-hierarchical weighting are closer to 1 than the corresponding ratios in hierarchical weighting [219],[162].

- **Reference point effect:** Depending on the reference point the same outcome may be framed as a gain or a loss (e.g., 5% increases in sales, when 4% or 6% was expected). Weights depend on the status quo of the decision makers (DM). Advantages and disadvantages are likely to have greater impact on preferences than gains or losses [220],[221]. Weights derived from equivalent improvements and equivalent losses are not necessarily similar [222],[162].

The proposed sensitivity analysis consists on evaluating the reference point effect, which is the most uncertain aspect of the both mentioned situations. Through the sensitivity analysis it is intended to prove the robustness and the stability of the developed system.

3.4.2 Risk assessment of selected technologies

As mentioned in the introduction of this chapter (page 90), the risk assessment procedure for the technology selected to remediate the contaminated site in study must be established once all aspects of its basic engineering phase are known. Only then its behavior can be evaluated under several possible scenarios, as this procedure evaluates the probability of occurrence and consequences of an unexpected event (either natural or associated to the operations during the remedial project), in a time space during and after the implementation of the restoration measures.

The following risk analysis was first compiled and applied at the *Kölliken Special Waste Deposit* site by the company CSD[1], taking into consideration several scenarios that conform

[1] CSD Ingénieurs Conseils SA. Ch. de Montelly 78, CP 60. 1000 Lausanne 20.

the final evaluation of the selected technological alternatives for site remediation. The evaluation consists on the determination of the risk degree for the selected technological alternative under several possible scenarios. The ranges of acceptable risks are defined in Table 35.

Table 35. Definition of acceptable risks for the assessed technologies.

Probability of occurrence	Consequences			
	Negligible	Medium	High	Very high
High				
Medium				
Small				
Very small				

Legend		
Acceptable risk	Transition range	Not acceptable risk

Table 36. Description of the different scenarios for the determination of the risk assessment for the selected technological alternative for site remediation and/or containment

Scenario	Description	Possible emission paths, endangered good
Scenario 1	Train accident by collision with a train or an obstacle.	Gas and Groundwater path
Scenario 2	Accident of a container when loading the carrier wagon.	Gas and Groundwater path
Scenario 3	Uncoiling of a container's rear door when lifting.	Gas and Groundwater path
Scenario 4	Failure of the ventilating system during the excavation (case of operations under roof).	Gas path
Scenario 5	Failure of the off-gas system on the site.	Gas path
Scenario 6	Loss of the off-gas system in the manipulation hall (case of operations under roof).	Gas path
Scenario 7	Fire in the contaminated site's body.	Gas and Groundwater path
Scenario 8	Fire in the deposit area.	Groundwater path
Scenario 9	Leaky container in the container deposit area.	Groundwater path
Scenario 10	Leaky barrel in the deposit area.	Groundwater path
Scenario 11	Substantial rise of waste water losses over the site base layer during remediation procedures.	Groundwater path
Scenario 12	Damage of the waste water logging system by landslide.	Groundwater
Scenario 13	Damage of the gas collection system by landslide.	Air

Table 37. Probability of occurrence of the defined scenarios

Probability	Qualitative description	Quantitative description
High	Common recurrent event	1 x per year
Medium	Occasional recurrent event	1 x per 10 years
Low	Rarely recurrent event	1 x per 100 years
Very low	Very rarely recurrent event	1 x per 1000 years

Table 38. Definition of the damage degree of the defined scenarios

Consequence		Impact	
		Humans	Environment
Very high	Catastrophe	Dead, injured	irreversible long period damages
High	Severe accident	Personal damages (injuries)	Partial re-establishment over years
Medium	Accident	Light injuries	Possible re-establishment in months
Negligibly	Incident	Irritation,annoyances	Possible re-establishment in days

The evaluation comprises four different aspects in the definition of scenarios: Disturbances of the railway connection (scenario 1 to 3), Uncontrolled gas outlets (scenario 4 to 8), Diffuse waste water losses (scenario 9 to 11), and Slope failure and landslide (scenarios 12 and 13). The considered scenarios are summarized in Table 36, page 95. For the definition of probability and consecuences, see Table 37 and Table 38, respectively. Although the introduced evaluation process cannot be generalized at this point, as it entails aspects of a further design step, it is important to consider it as an example of model to determine the appropriateness of a certain technology. Furthermore, the use of a matrix-based risk assessment procedure that determines the susceptibility of the technology under undesired events can ensure the acceptance of the community and stakeholders, as it could bring a degree of transparence in the technology selection process.

3.5 Application of the developed system to the Chilean situation as a know-how transfer tool for developing countries

In most South American countries, the subject of contaminated sites is a new environmental issue that authorities have just started to deal with. There are cases like the State of Sao Paulo (Brazil), in which this subject has already been developed and established, and norms and regulations for contaminated sites are already at hand. In such cases, a strong know-how exchange has been provided from industrialized countries to accelerate the adaptation of the existing regulations and norms to the reality of the region, as well as the subsequently implementation of the local legal framework [32].

The case of Chile presents currently an interested environmental-normative body that has started to prepare the country's legal context as well as to foster the formation of research and investigation groups that will deal with the exploration, investigation and management of contaminated sites at regional as well as national levels [33],[34]. New regulations have been just started to form the new legal framework in which the management activities for contaminated sites will take place. The Chilean contaminated sites situation up to this date has not yet been explored, neither concerning the number and location of the potential contaminated sites, nor concerning the associated risks upon human health and environment. This situation is certainly a great liability but also a challenge for the planning and decision-making phases in contaminated sites management. There is therefore the urgent need of a comprehensive technical and legal support in this stage.

International experience has demonstrated that a methodology to establish the hierarchy of the potentially contaminated sites is an essential issue for technical and economical reasons, as it is not possible to include all (suspected) contaminated sites simultaneously into an intensive evaluation process. This hierarchy procedure must be sustained by a solid technical basis, allowing determining the sites that may have a greater impact on the human health and environment. On the other hand, it must provide with a reasonable suggestion on general management measures (i.e. remediation, containment, monitoring, suggestion of further monitoring and evaluation, or to register as harmless) to practice at each individual site suspected of contamination [5],[20].

Since 2003, the Chilean National Environmental Commission (CONAMA) has worked on the identification of priority regions to perform the first evaluation of the national contaminated sites situation. The VIII Region of Bio Bio (Figure 50, page 97), due to its social and economic importance at a national level, has been selected as one of these priority regions.

Main goal of this above mentioned work is to provide with a register of (suspected) contaminated sites in the Region of the Bio Bio, particularly in the provinces of Concepción and Arauco, defining a methodology for the risk assessment, identification and hierarchy of sites suspected of contamination.

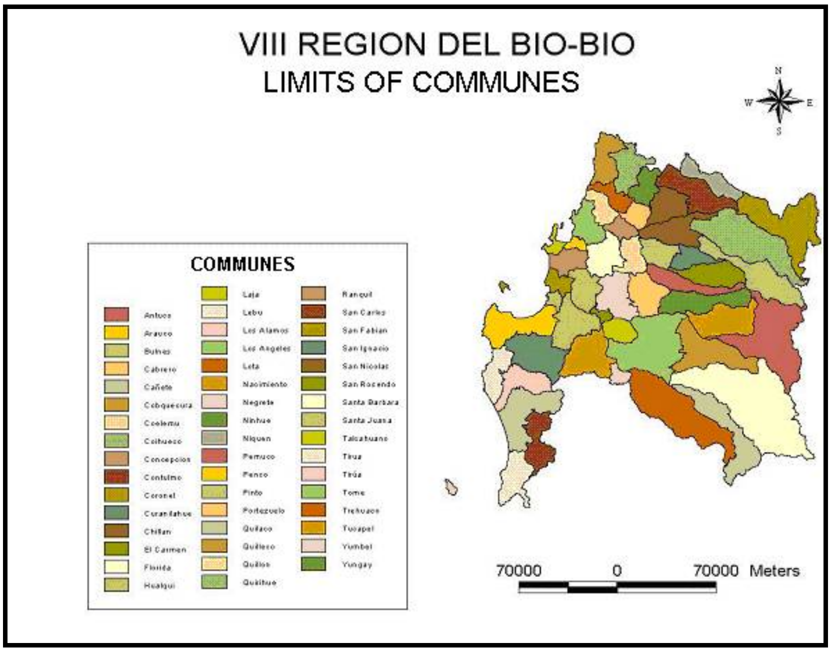


Figure 50. Political map of the VIII Region of Chile.

3.5.1 Description of the Study Area: VIII Region of the Bio Bio, Chile

The Eighth Region of the Bio Bio is located between 36º 00’ and 38º 30’ Latitude South, and from the 71º 00’ Longitude West until the Pacific Ocean. Its total surface adds up to 37,062.6 km². Its capital is the city of Concepción, and it is divided into four provinces: Ñuble, Bio Bio, Concepción and Arauco, which add up a total of 52 communes and a total population of 1,861,562 inhabitants. The regional economy is based on strong exporting forest-, fishing- and chemical industries. In terms of population and productivity, as well as from its culture and educational activities, this is the second most important Region of Chile, after the Metropolitan Region [225],[226].

Population and industrial growth of the Region of the Bio Bio has derived in an accelerated raise of the amount of residues, generating a serious environmental issue. The Region presents a strong industrial activity associated to forest, fishing, food production, metallurgy and chemical industry. The distribution of the different main industrial activities in the Bio Bio Region is mainly based on the availability of resources and raw materials for its development. The industrial activities that are carried out in the VIII Region, and which are considered as potential sources of soil and water contamination, are listed as follows.

- Basic steel industry
- Packaging of fish, crustaceans and other marine products
- Fish flour production
- Sugar manufacture and refinement
- Dyes and finished textiles production
- Sawmills
- Board and Fiber Panels production
- Pulp, paper and cardboard manufacture
- Production and refinement of chemicals
- Petroleum refinement
- Cement, Lime and Plaster production
- Manufacture of metallic products
- Treatment of industrial and domestic wastes
- Milk and milk products industry
- Glass manufacture
- Marine shipyards and arsenals.

The large number of industries present in the zone opens a broad range of potential sources of contamination for soil, surface- and ground waters, as these activities generate different types of solid, liquid and gaseous remainders, many of which are not treated suitably by lack of environmental conscience of their emitting sources. On the other hand, the high concentration of industries located in the surroundings of urbanized sectors, mainly in the province of Concepción, is an incentive to carry out a study on the impact of different wastes on different environmental goods such as soil, surface- and ground waters. The type of industrial activities that are carried out in the VIII Region, as well as their distribution (out of a total of 157 companies) are presented in Figure 51 (see page 99).

According to recent studies [227], the total amount of industrial wastes produced in the Region of the Bio Bio amounts to about 350,000 tons per year. Most of the generated waste corresponds to the forest sector (including sawmills and pulp and paper, cardboard, chip-boards and other companies), and the iron and steel industry. These industries comprise 21% and 17% of the regional waste generation respectively. Some industries of the zone (e.g. textile production) do not generate great volumes of wastes, but these are characterized by their high toxicity and a high impact on the sites where they are deposited. A similar situation, but on a larger scale, occurs in the petroleum refineries, which generate only around 1% of the zone's waste, but these wastes constitute a serious problem due to their toxicity and their storage, as they have been accumulated in the hope of a future profitable use.

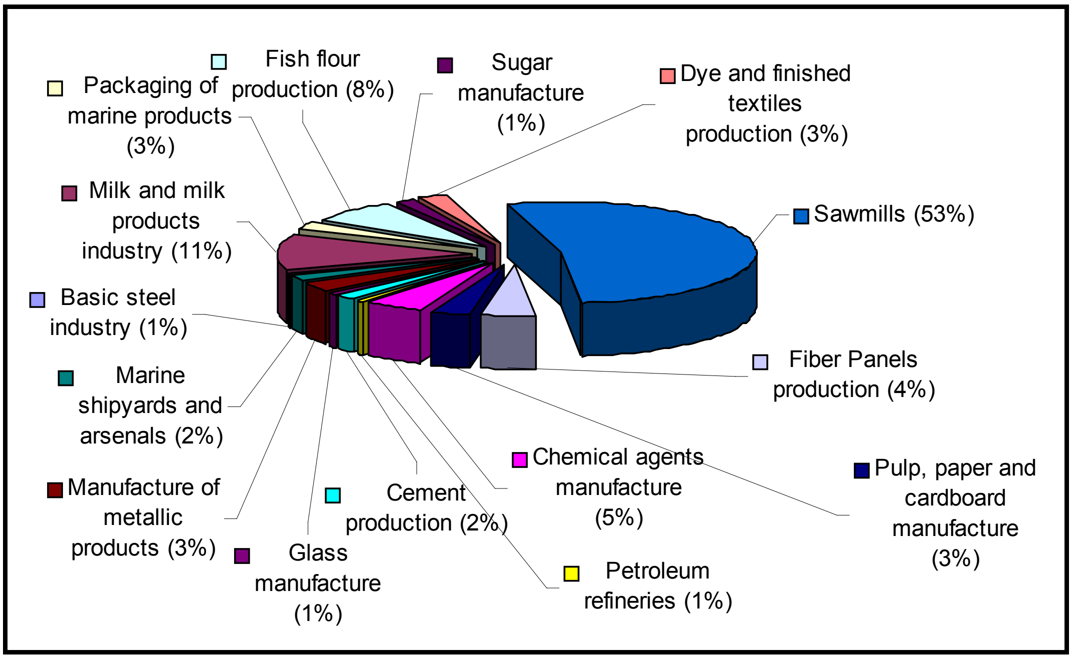


Figure 51. Industrial activities in the Region of the Bio Bio, Chile.

3.5.2 Methodology addressed in the study

The strategy followed in this study corresponds to a combination of the identification method proposed by Fundación Chile [228] with the investigation and evaluation processes for potentially contaminated sites (SPC) used currently in European countries such as Austria and Germany [211],[229]. In general terms, the methodology consists in the following steps, which can be observed in Figure 52 (see page 100):

- Development of a list of Sites Potentially Contaminated (SPC). This list will be done on the basis of the developed activities at the different zones, and with the collected historical data, as well as with the data delivered by the Operative Committee on Contaminated Sites for the Region of the Bio Bio[1].

- Identification of areas of interest, on the basis of the vulnerability of the environmental goods. In this work, the environmental goods appointed correspond to soil, groundwater and the health of the population.
- Performing a first priority evaluation and risk assessment for all identified SPC.
- Development of a Site Inspection Plan, from which all information needed for a second risk assessment evaluation could be gathered or generated.
- Applying the Inspection Form to the SPC identified in the first evaluation.
- Performing the second risk assessment in order to priorize and classify the identified SPC.

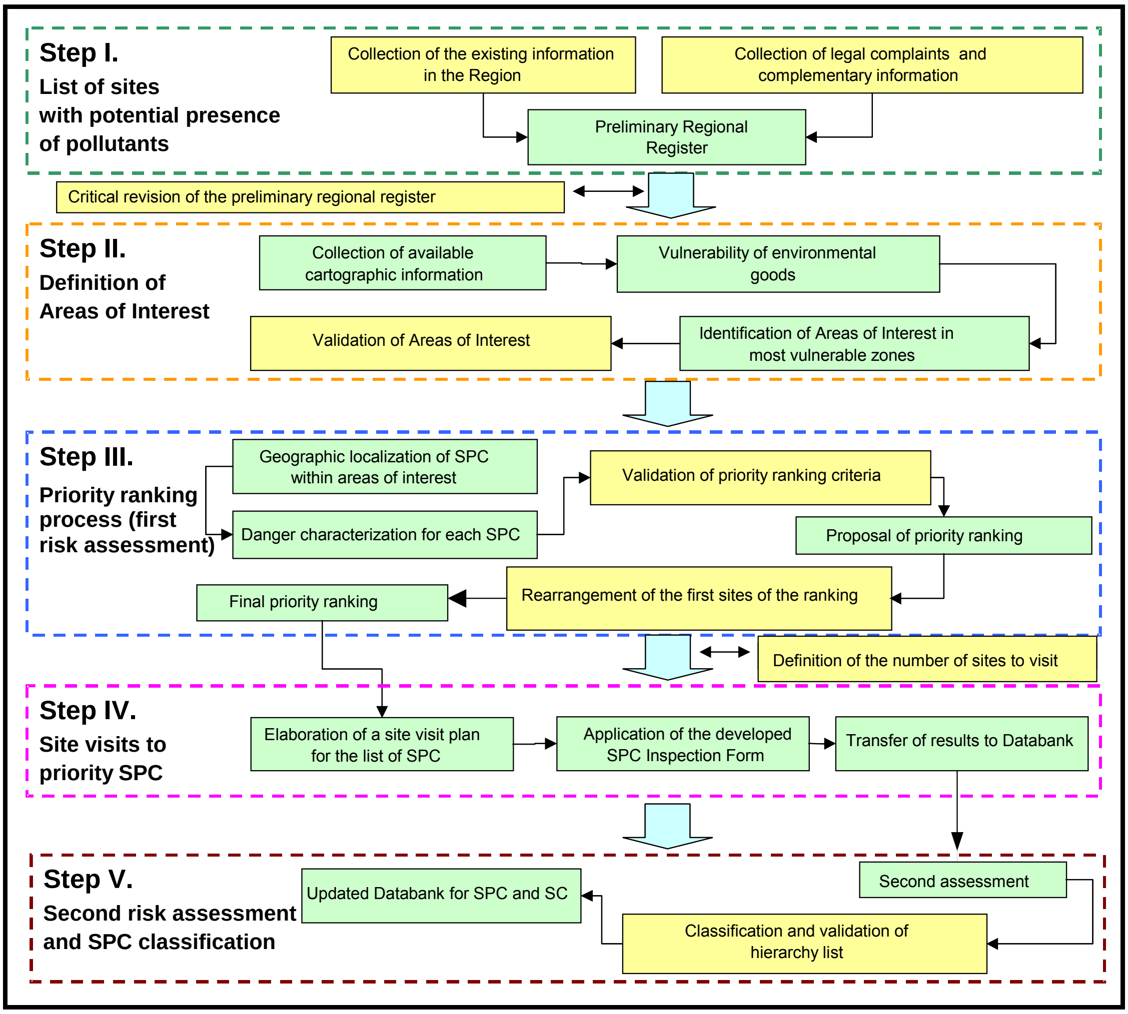


Figure 52. Flowchart of the general methodology for the identification and classification of sites potentially contaminated (SPC) as suggested by Fundación Chile [228].

[1] The recently established Operative Committee on Contaminated Sites for the VIII Region of Chile is composed by: Servicio Agrícola y Ganadero (SAG), Dirección Regional de Aguas, Servicio Nacional de Geología y Minería, Servicio Regional Ministerial (SEREMI) de Salud, SEREMI de Agricultura, Corporación Nacional Forestal (CONAF), all the consulted Municipalities, Superintendencia de Electricidad y Combustibles, **Universidad de Concepción**, and CONAMA VIII Region.

The present study has been carried out within the context of certain limiting factors, which constrain the possibility to include all the required data for a complete identification and priorization of sites with potential presence of pollutants in the whole Region. First, the lack of technical and economic resources, as well as a short period of time in which the study had to be carried out, have made that only the provinces of Concepción and Arauco could be envisaged, leaving aside the analysis for the two remaining provinces of the Region (Bio Bio and Ñuble). Another aspect that limits the study is the deficit of information and resources in certain studied zones of the Region, constituting a limiting factor to obtain a complete application of the process. This is mainly observed in the rural and isolated areas, where the required thematic information associated to contaminated sites (e.g. local data bases, demands and registers, etc.) is not available. The present work therefore considers the information that currently exists and is available in the Region, regardless if it is exhaustive and comprehensive or scarce and inexact.

Finally, the conducted present work has been limited to potentially contaminated sites, i.e. those whose contained substances are susceptible to constitute a risk for human health and/or for the preservation of nature (environmental receptors). This means that a site potentially contaminated by noise or levels of radiation (which are also part of the definition of contamination according to the General Fundamentals in Environmental Issues, Chilean Law Nr. 19300) will not be considered for evaluation.

3.5.3 Identification of sites potentially contaminated (SPC) in the Region of the Bio Bio, Chile

For a proper identification of SPC, it is imperative to count on reliable information. In this work a series of public services were consulted, depending on the required data. The consulted services and the information acquired from them is presented in Table 39.

Table 39. Information sources for preparing the register of sites potentially contaminated (SPC) in the Bio Bio Region.

Type of Information	Source [a]
List of Industrial Establishments	University of Concepción, SEREMI of Health
List of Landfills and Illegal Dumping Sites	CONAMA
List of SPC, province of Arauco	CONAF
List of Environmental Liabilities VIII Region	CONAF
List of SPC, Commune of Coronel	Municipality of Coronel
List of Petrol Stations VIII Region	SAG, INFOR
List of Mining Environmental Liabilities	SERNAGEOMIN

[a] SEREMI: Regional Ministry Service, CONAF: National Forest Corporation, SAG: Agriculture and Cattle Service, INFOR: National Forest Institute, SERNAGEOMIN: National Service on Geology and Mining.

In order to obtain a better differentiation of the SPC register, CONAMA has defined five activities and/or commercial branches, which are listed as follows:

1. Industrial Activities.

2. Landfills and Illegal Dumping Sites.
3. Environmental Liabilities (receptors of contamination).
4. Mining Activities (Mining Environmental Liabilities).
5. Petrol Stations and Hydrocarbons Storage Zones.

The collected information was classified according to the above listed categories. The data required in every step of the project can be derived from Figure 52 (page 100). All the collected information composes the first register of SPC for the VIII Region of Chile.

3.5.4 Risk assessment methodology and classification of sites suspected of contamination

The conducted methodology follows the risk assessment procedure elaborated in chapter 3.2, consisting in a two-step evaluation process. The first step corresponds to a preliminary assessment according to historical data collection on soil use and/or industrial activity. The second risk assessment procedure corresponds to the evaluation made according to the data collected in site visits. A site inspection form has been developed, which has to be filled up by the responsible person for evaluating the site (refer to Annex VII).

As a result of this process, the identified sites under suspicion of contamination in the VIII Region of Chile will be classified according to their endangerment priorities. According to these results, the dimension of the contaminated sites problem can be estimated and characterized.

3.6 Synopsis of Chapter 3

The proposed knowledge-based tool for the remediation of contaminated sites entails the development of a three-step system for the determination of the most appropriate technological alternative. Chapter 3 has introduced the description of each step of the system, composed by a two-step risk assessment procedure, a module for the identification of suitable technologies for each site and a final module for the determination of the most appropriate technology according to the priorities of all stakeholders involved in the project.

Chapter 3 also introduces the methodology applied to conduct the first studies on the determination of the contaminated sites dimension in a Chilean industrial Region. This work, carried out in conjunction with the University of Concepción and the Chilean National Environmental Commission, implied the utilization of the first module of the proposed knowledge-based tool for the evaluation of the identified sites under suspicion of contamination.

The resulting proposed methodology and its validation, as well as the results of the conducted studies in Chile and the discussion that they arise will be presented in the following chapter.

4 Results and discussion

According to the described or elaborated methods and the practical approach to develop a knowledge-based decision system for the management of contaminated sites, the following sections introduce the obtained results of this work.

First of all, the description of the developed knowledge-based system is presented, divided into its three main branches, namely the risk assessment module, the module for identifying the suitable technologies for the management of the sites classified as risk-posing to the environment and the human health, and finally the module for the determination of the most appropriate technology to be used according to the hierarchy elicitation performed by the decision maker(s). This chapter also introduces the sensitivity analysis conducted to determine the stability and robustness of the developed system. Subsequently, this chapter introduces a process for the determination of the validity of the system when tested against three conducted projects in Austria: an industrial site, an industrial waste landfill and a municipal solid waste landfill.

This chapter also introduces the results of the land register process for the Region of the Bio Bio in Chile, which aims to obtain an overview of the actual contaminated sites situation in the Region and an approximate endangerment classification of the sites under suspicion of contamination located in the most vulnerable areas. Finally, considering the identified contaminated sites situation in the Region, this chapter presents the activities needed for a future application of the knowledge-based tool in Chile, as well as the basics of a potential technology and know-how transfer process regarding the adaptation of the environmental regulations and the state-of-the-art site management technologies introduced in Chapter 2 and Chapter 3.

4.1 Module for risk assessment of suspected contaminated sites

The risk assessment module has been integrally developed in a Visual Basic environment, in order to obtain a friendly end-user interface. The system contemplates two phases of risk assessment, which have been programmed separately. The following sections introduce the developed modules for the implementation of the risk assessment evaluation.

4.1.1 First risk assessment module

The first risk assessment process contemplates the features described in the materials and practical approach section of chapter 3.2.1. The end user deals with a simple form to fill up (Figure 53), from which the system calculates the endangerment potential as described in chapter 3.2.1. The parameters that must be completed by the end user are the following:

- Type of activity carried out at the site
- Extension of the site
- Number of endangered environmental goods
- Type of endangerment for soil and groundwater, as means of direct and indirect influence to the human health in their surroundings.

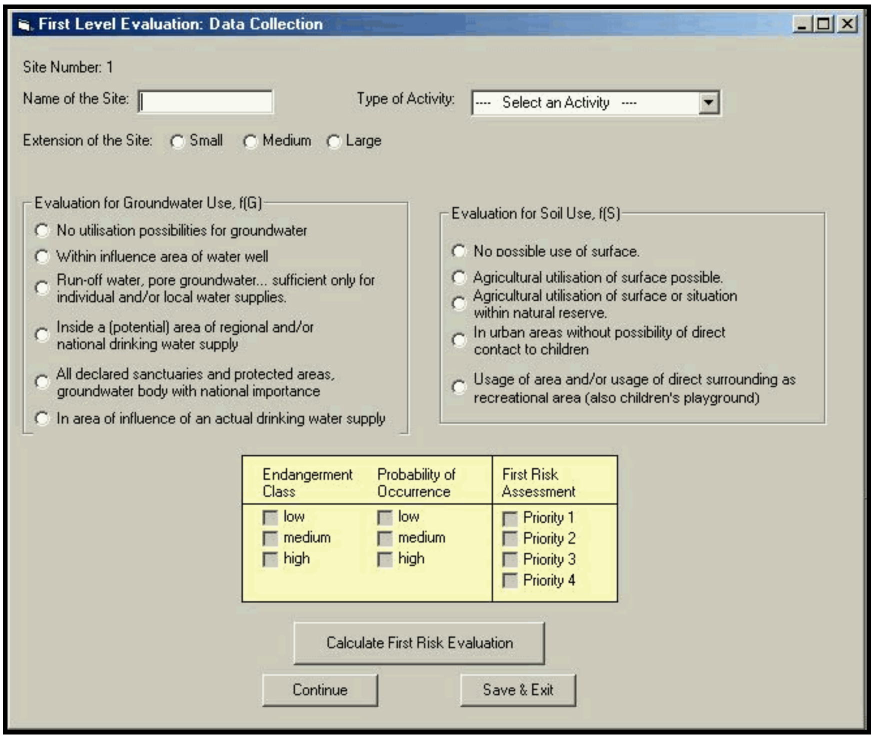


Figure 53. User interface developed for the first risk assessment evaluation.

The system includes the possibility to differentiate industrial activities from waste disposal activities, as different calculation procedures are distinguished. A total of 26 industrial activities have been included in the evaluation (chapter 3.2.1), each of them having an associated probability value of occurrence regarding their endangerment potential, as it is observed in Table 15. Moreover, four classes of disposal activities have been considered for evaluation, all of which have also been presented in chapter 3.2.1. The calculation procedure and/or value for determining the material danger of each activity, being a disposal or industrial activity, follows the indications given in chapter 3.2.1.

After the evaluation of the risk potential of all investigated sites, the program generates a text file that can be exported to as a MS Excel Worksheet in a template prepared for this purpose. In this worksheet, resulting values of the calculated risk associated to each site are presented, along with all the interim parameters calculated during the operation. The final result of the first assessment module is the determination of the sites with the highest priority to be evaluated in the second step of the risk evaluation. As an example, Figure 54 presents graphically the determination of the sites which are classified within the four possible priorities defined in chapter 3.2.1., where blue columns represent sites with a resulting hierarchy of Priority 4 (i.e. no priority).

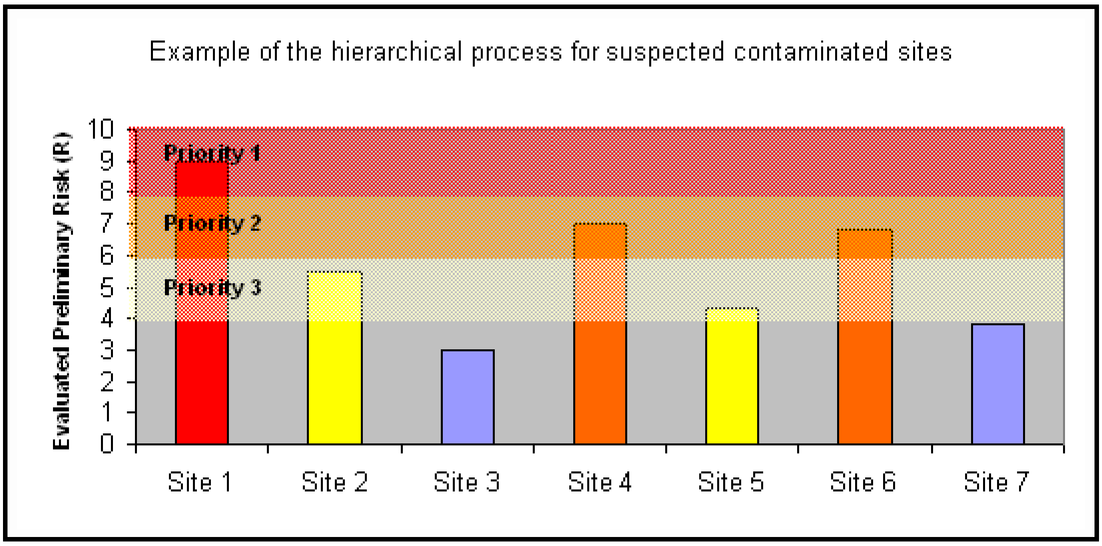


Figure 54. Example of the hierarchical process for suspected contaminated sites performed in the first evaluation module.

4.1.2 Second risk assessment module

The second risk assessment process contemplates the calculation described in the materials and practical approach, chapter 3.2.2. This second assessment has also been buit in a Visual Basic environment. The program user shall enter the information regarding the activities taken place in the site. A friendly user interface has been developed for the proper entry of data, regarding:

- material danger caused by substances (S-Value),
- site-specific local conditions (V-value),
- toxicological risk (H-Value),
- characteristic land use (N-Value).

The end user deals with simple forms to fill up (Figure 55, Figure 56 and Annex IV), from which the system calculates the endangerment potential as described in chapter 3.2.1. As it may be observed, the forms are user-friendly and simple. This has been intentionally done, in order to allow all kinds of stakeholders and decision-makers to provide information, without requiring special help for these purposes.

A fair critic to the proposed risk assessment procedure is its lack of quantitative calculations, as it represents a simplification of the Baden-Würtemberg model for assessing contaminated sites. This situation may derive in an inexact evaluation of the actual endangerment value of a site under suspicion of contamination. Nevertheless, since one of the main goals of this work is to propose a first, simple and qualitative procedure for the determination of the Chilean contaminated sites situation, in order to focus the future limited budgets for remedial projects in contaminated sites, the proposed evaluation has been considered an appropriate tool. A further development of this tool should contemplate the establishment of a **risk matrix evaluation**, in which the risk priority is determined in one step, considering the actual *probability of occurrence* and *expected consequences* of the pollution propagation from a contaminated site. Such evaluation using a risk matrix could then be considered as a state-of-the-art, more accurate risk assessment process.

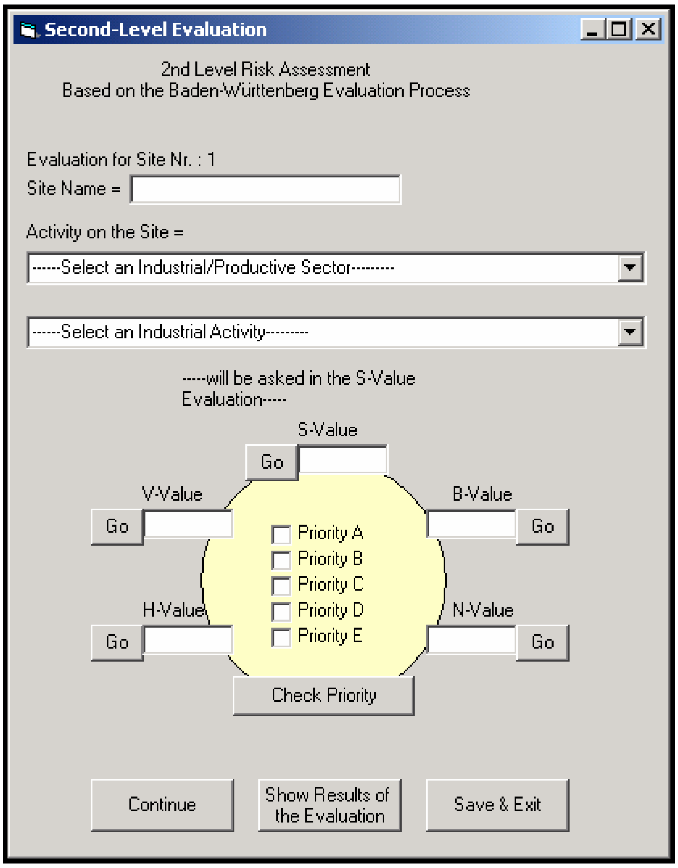


Figure 55. User interface developed for the second risk assessment evaluation module.

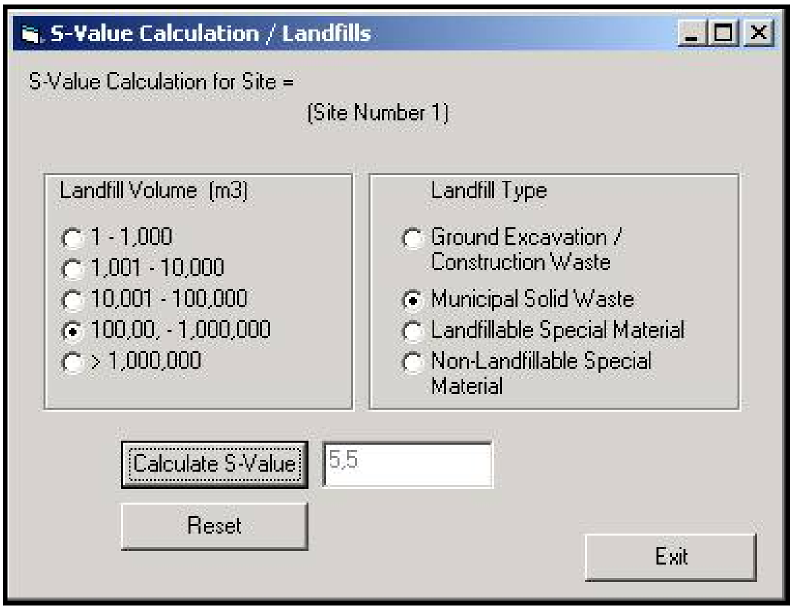
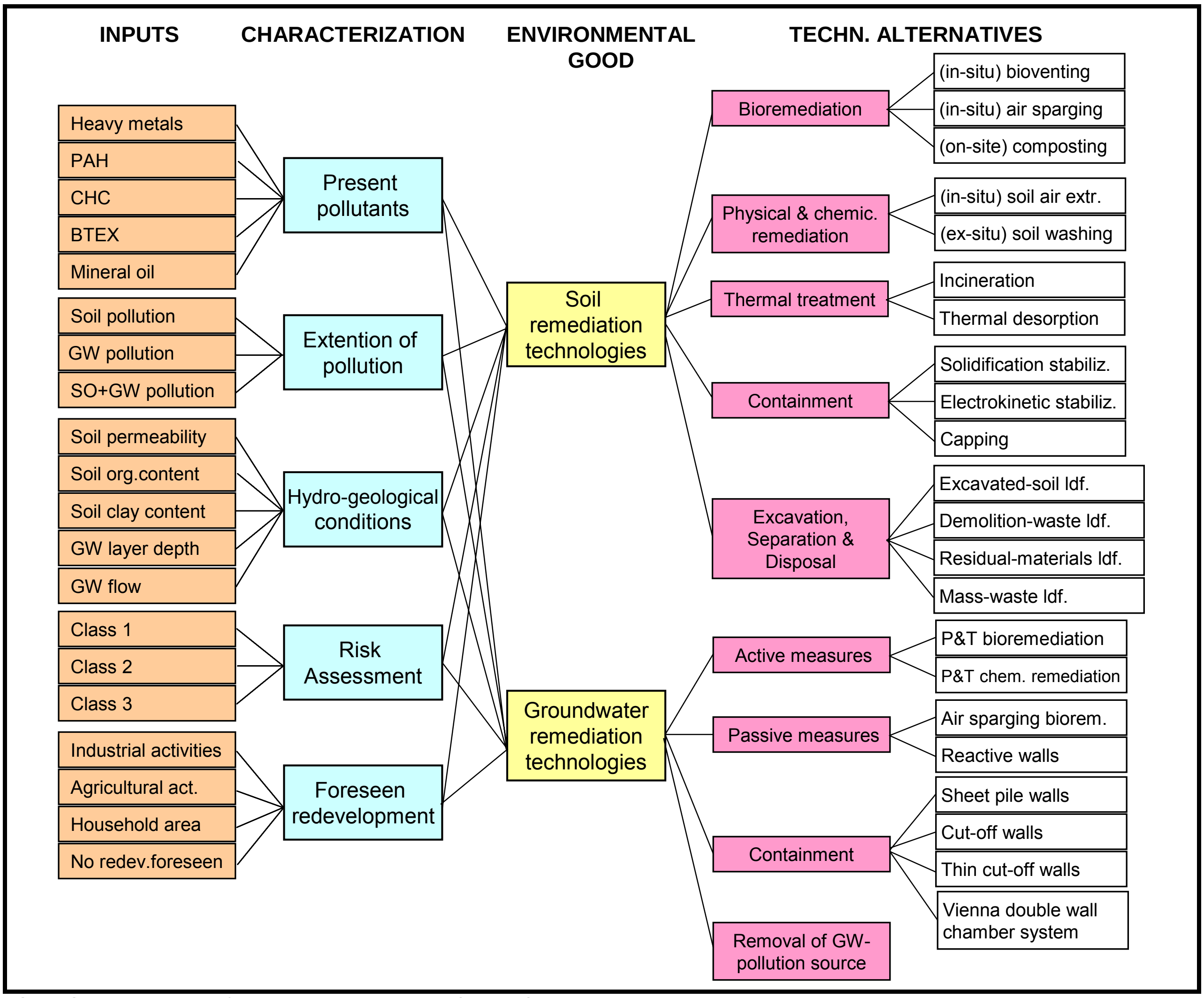


Figure 56. Form for the calculation of the material danger for landfills.

4.2 Module for selecting feasible technological alternatives for site remediation

4.2.1 General parameters necessary for the evaluation

The first step for the determination of the technologically feasible remedial options for a contaminated site consists in the characterization of the site in terms of its hydrogeological conditions as well as the pollutants present and the extension of the contamination. A number of specific factors and constraints will impact more or less directly the decision making process, such as: remediation objectives (e.g. envisaged land use), economic factors (e.g. employment, infrastructure), environmental impact, public perception/acceptance and public participation, risks affecting remediation technologies, occupational hazards, costs, funding, and availability of resources, and regulatory aspects, such as cleanup standards and competing legislation [231].



GW: Groundwater; P&T: Pump and Treat; ldf.: landfill

Figure 57. Overview of the parameters for site characterization and the addressed technologies evaluated in the model.

From these, the selected parameters for site characterization as well as the technologies for evaluation are presented in Figure 57. The pollutants considered in this evaluation have been selected as they are the most commonly occurrent in industrial contaminated sites as well as abandoned landfills. Type and concentration of these substances will quantitatively characterize the site in terms of the volatility of the contaminants as well as the degradation possibilities when a certain technology is evaluated. The extension of the pollution and the hydrogeological conditions will determine whether a containment of the site is needed to prevent further propagation of the contaminants into the aquifer. Soil parameters such as permeability as well as clay and organic content will be determinant for the selection of the remedial options among ex-situ and in-situ technologies. With the introduction of the foreseen development, if any, the standards or targets for the remediation can be set. As presented in the following sections, there are different considerations for the final use of the site depending on the limits of certain pollutants remaining at the site. The addressed technologies represent a set of options most commonly used in remedial projects. Among them it is possible to identify in-situ, ex-situ, as well as on-site and off-site alternatives.

4.2.2 Development of the decision procedure

After obtaining the characteristics of the site, the procedure to select the suitable technologies can be started. Decision flowcharts have been established taking into consideration different proved models tested in field studies along the past decade. By following these decision flowcharts (Figure 58) it is possible to determine the following steps:

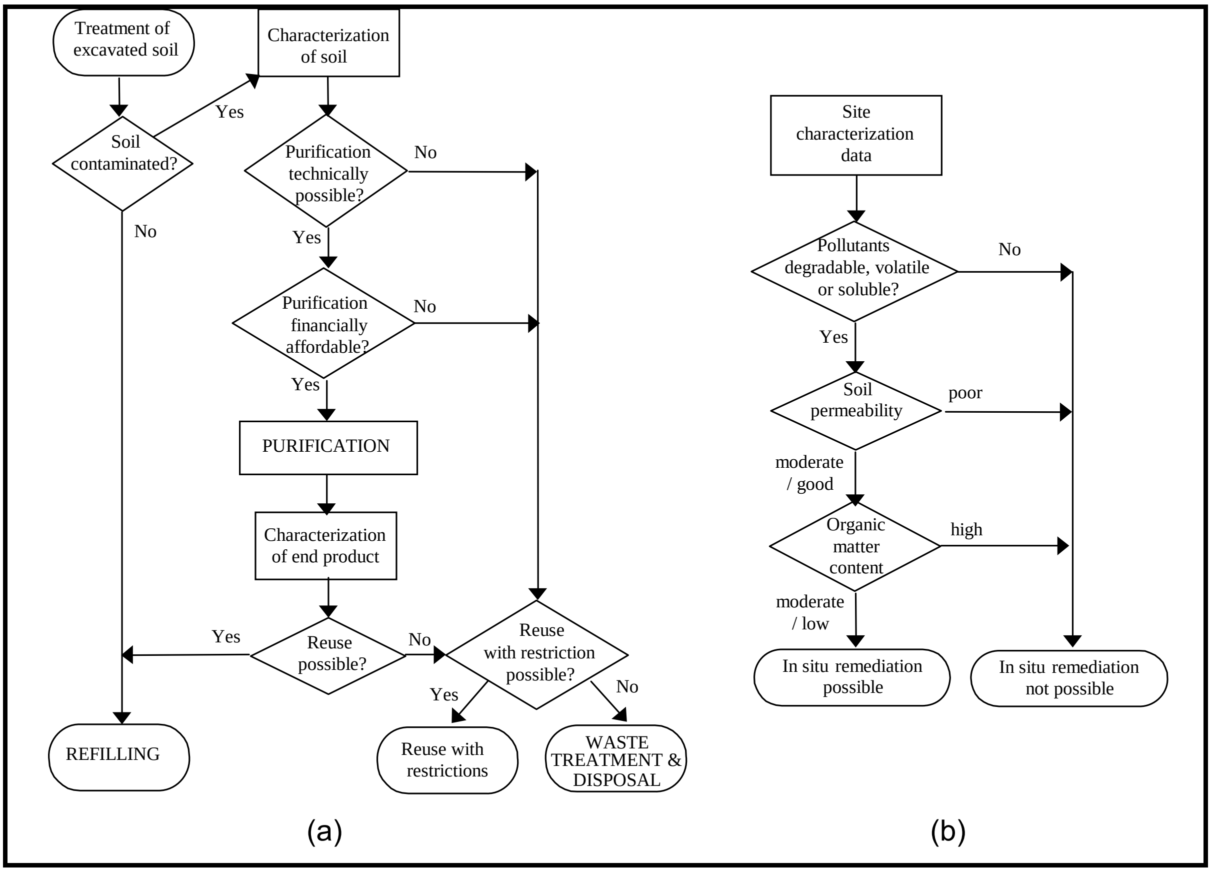


Figure 58. Decision trees for soil remediation: (a) Treatment of excavated soil (b) Suitability of in-situ remediation techniques [198]

- Step 1: Evaluation of the technical suitability of remedial options
- Step 2: Determination of possible process combinations and evaluation of performance and associated project costs
- Step 3: (In cooperation with all involved project stakeholders) Establishment of the budget constrains, as a "knock-out criteria" for the selection of a remedial alternative.

4.2.2.1 Determination of the technical suitability for remediation technologies

The first step of the process consists on the determination of the technical suitability of the different technological alternatives for remediation. This evaluation is made taking into account the soil properties (organic content, pH, clay composition, permeability), the pollutants present and their concentration, and the intended site future use.

The concentration of the pollutants is first categorized into the scores of "Low", "Medium" and "High". For this purpose the factor *Nconc* is introduced, which is defined as the ratio between the present pollution and the permitted value according to the land use (Annex VI), which allows to define different restrictions according to the site future reuse (Table 40). It is defined that the maximum concentration of a pollutant to accept at a site corresponds to 50 times their allowed concentration (i.e., $Nconc_{max}$ = 50). The concepts of characterization of contamination are determined by:

- Low concentration: Nconc < 0.1·$Nconc_{max}$
- Medium concentration: 0.1·$Nconc_{max}$ < Nconc < 0.8·$Nconc_{max}$
- High concentration: Nconc > 0.8·$Nconc_{max}$

Table 40. Calculation of $Nconc_{max}$ according to the intended reuse of the site

Pollutants	Limits for production places [mg/kg ds]	Limits for living places [mg/kg ds]	$Nconc_{max}$ [-]	
			Prod. places	Living places
PAH	1	1	50	50
HM	40	70	20,00	3,500
BTEX	6	6	300	300
Hydrocarbons	50	200	2,500	10,000

Once the pollution degree is known for each contaminant present in the site, the determination of the solubility and volatility of the present mixture is performed, based on Table 41. In this case a fuzzy set of rules has been developed in order to provide an orientation of the actual conditions on the site, considering additionally the pH conditions on the site (especially concerning the presence of heavy metals contamination). The incorporation of a fuzzy logic approach allows translating the actual values of the selected parameters into a natural language of qualification. Therefore, a set of membership functions (i.e., pollutants concentration, extension of the site, pollutants volatility) has been developed to determine the conditions of the site in a natural language. The use of the Fuzzy Logic Toolbox of MatLab ® [202] introduces the mathematical tools to work with these functions.

After determining the volatility and solubility of the contaminants present in the site it is possible to determine whether in-situ possibilities can be applied in the site. This is done by considering the conditions provided in Figure 58b, the results of the fuzzy determination of the forementioned parameters, and the indications from Table 41.

Table 41. Contaminant information on in situ treatment (taken from [198] and modified)

Contamination	Volatility	Biodegradability		Solubility	In situ possibilities
		Aerobic	Anaerobic		
Hydrocarbons					
Gasoline (C_4-C_{12})	+	+	-	±	yes
Kerosene (C_6-C_{15})	±	+	-	±	yes
Gasoil (C_9-C_{26})	-	±	-	- *	yes
Domestic fuel (C_9-C_{24})	-	±	-	- *	yes
Lubricants (C_{15}-C_{40})	-	-	-	-	no
Aromatics (BTEX)	+	+	±	±	yes
PAH					
Light (2-3 rings)	±	+	-	± *	yes
Heavy (4-5 rings)	-	-	-	- *	no
CHC					
Aliphatic (PER, TRI)	+	-	+	±	yes
Chlorobenzene	+	+	-	±	yes
Pesticides	-	±	-	-	no
PCB	-	-	-	-	no
Heavy metals	-	-	-	± *	no

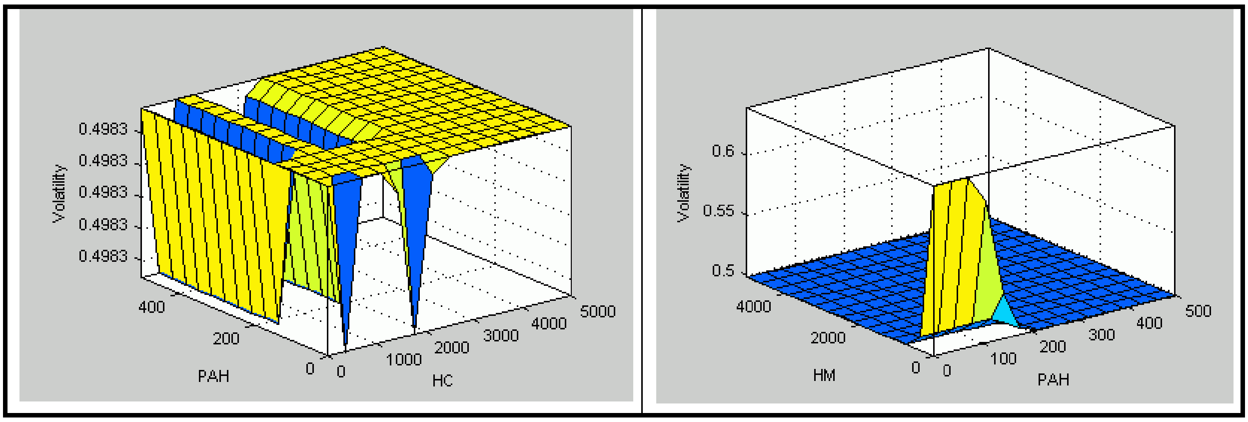


Figure 59. Fuzzy rules under MatLab environment for the determination of the volatility and solubility of pollutants mixtures present in a contaminated site.

The next step considers the present pollutants, their characterized concentration (in terms of Low, Medium and High values) and will determine the suitability of the main groups of remedial options (see Table 33 for details): Bioremediation, Physical and Chemical, Thermal, Containment, and Excavation and Disposal measure. The following set of rules shown in Figure 59 and Figure 60 will determine the technical feasibility for applying these remedial options for the remediation of the contaminated site. These rules have been conformed based on the experience in Germany and Austria, which is summarized in Table 42 and Table 43.

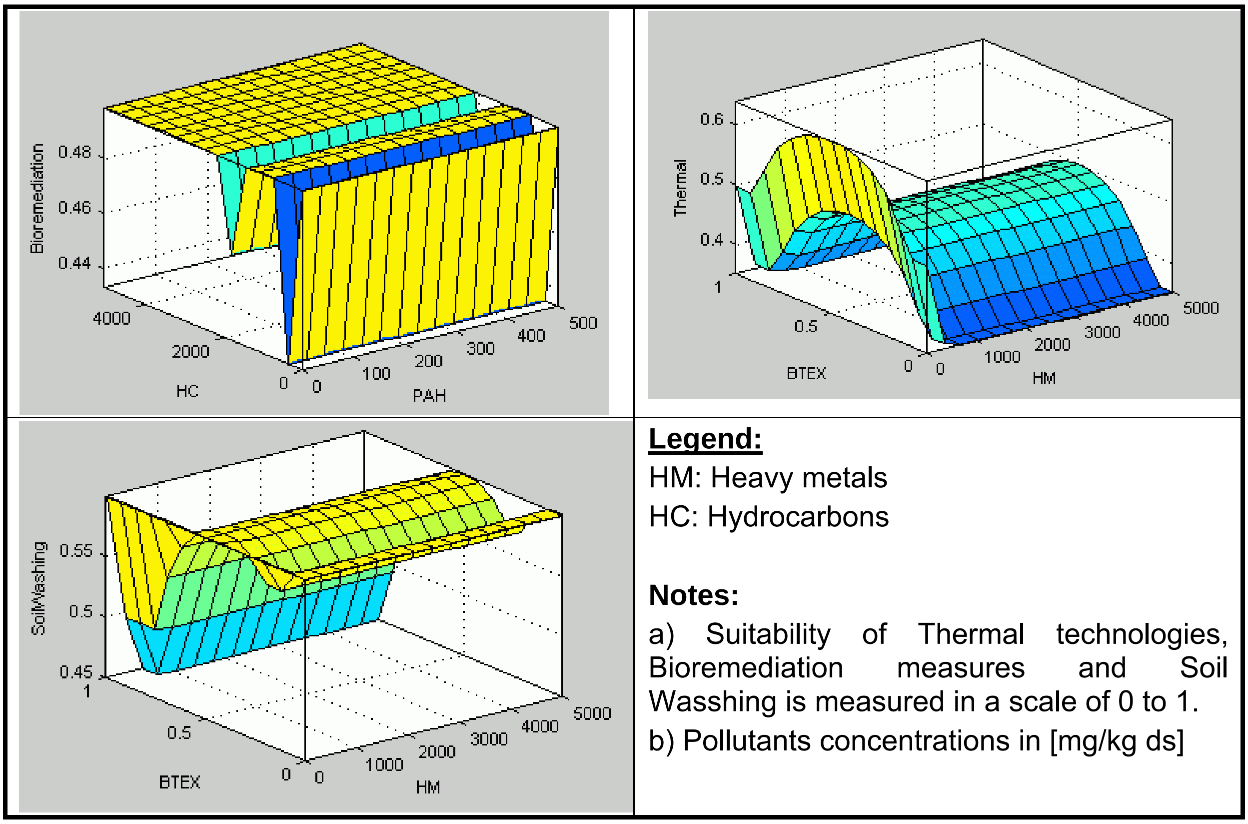


Figure 60. Examples of the fuzzy set rules for the determination of the technical suitability of the remedial options (ordered by groups)

The data summarized from Table 41 to Table 43 form the basis for an analysis of the classes of contaminants treated by each technology type at remedial action sites. Halogenated volatile organic compounds (VOCs), BTEX, and non-halogenated VOCs are being treated most often by soil vapor extraction (SVE). Non-halogenated semivolatile organic compounds (SVOCs) and polycyclic aromatic hydrocarbons (PAHs) are being treated most often by bioremediation. PCBs and halogenated SVOCs are being treated most often by incineration. Metals are being treated almost exclusively by solidification/ stabilization [81].

Table 42. Remediation technologies for Heavy Metals (taken from [207] and modified)

Remediation Process	Process feasibility for Heavy metals	Costs	Pollutants removal
MBP	-	-	-
THP	-/+ (1)	+++	++
WP	++	++/+++	++
Precipitation	+/++	++	++
AS	-	-	-
ACA	-/+	-/+	-/+
BHR	-	-	-
B-/AS	-	-	-
CHO	-	-	-
IE	+/++	++	++
RW	++	+++	++
NA	+	+	+

Used Simbology

Used Abbreviation / Description of Remediation Process

MBP	: Microbiological process	BHR	: Biological hydraulical remediation
THP	: Thermal process	B-/AS	: Bio-/Air Sparging
WP	: Washing process	CHO	: Chemical oxidation
MSP	: mechanical separation process	IE	: Ion exchange
AS	: Air stripping	RW	: Reactive walls/Funnel and gate
ACA	: Active Carbon Adsorption	NA	: Natural attenuation

Feasibility for Chemical Group		Costs		Pollutants removal	
-	not suitable	-	not relevant	-	Materials stay unchanged on site
+	limited	+	low	+	Materials are fixed/partially removed
++	suitable	++	medium	++	Materials are removed
+++	very suitable	+++	high	+++	Materials are destructed/ degraded

(1) Very limited. Where necessary, possible for mercury.

Table 43. Application suitability of remediation technologies for treating BTEX, Mineral oil, CHC, PAH and Phenole. Taken from [207] and modified.

Remedial Process	BTEX			Mineral oil			CHC			PAH			Phenole		
	FE[a)]	CO	PR	FE	CO	PR	FE	CO	PR	FE	CO	PR	FE	CO	PR
MBP	+	++	+++	+++	++	+++	+	++	+++	+	++	++	+	++	+++
THP	++	+++	++/+++	++	+++	+++	++	++/+++	++/+++	++	+++	+++	++	++	++/+++
WP	++	++/+++	++	++	++/+++	++	++	++/+++	++	++	++/+++	++	++	++/+++	++
MSP	+	+/++	++	+	+/++	++	-	-	-	-	-	-	-	-	-
AS	++	++	++	-/+	-/++	-/++	++	+	++	-	-	-	-	-	-
ACA	++	++	++	++	++	+	++	++	++	+	++	++	+++	++	++
BHR	++	++	+++	++	++	+++	-/+	-/++	-/+++	+	++	+++	++	++	+++
B-/AS	++	++	++/+++	+	++	++	+	++	++	-	-	-	-/+	-/++	-/++
CHO	++	++	+++	++	++	+++	+	++	+++	+	++	+++	+	++	+++
IE	-	-	-	-	-	-	-	-	-	-	-	-	-/+	-/++	-/++
RW	+	+++	++/+++	+	+++	++/+++	++	+++	+++	+	+++	++	+	-/++	++/+++
NA	++	+	+++	+++	+	+++	+	+	+++	+	+	+++	++	+	+++

Used Simbology

Used Abbreviation / Description of Remediation Process		Process feasibility for Chemical Group	Costs	Pollutants removal
MBP : Microbiological process THP : Thermal process WP : Washing process MSP : Mechanical separation process AS : Air stripping ACA : Active Carbon Adsorption	BHR : Biological hydraulical remediation B-/AS: Bio-/Air Sparging CHO : Chemical oxidation IE : Ion exchange RW : Reactive walls/Funnel and gate NA : Natural attenuation	- not suitable + limited ++ suitable +++ very suitable	- not relevant + low ++ medium +++ high	- Pollutants stay unchanged on site + Pollutants are fixed/partially removed ++ Pollutants are removed +++ Pollutants are destructed/ degraded

[a)] FE: Feasibility; CO: Costs; PR: Pollutants removal

As already mentioned in chapter 4.2.2, the use of the parameters risk classification and foreseen development of the site will determine the urgency (and therefore the need of temporary site containment measures) and the limit values to be achieved by the remediation technology. The latter is considered as a knock-out value for the elicitation of the technologies found suitable in the first step of the evaluation, in terms of the efficiency required for the evaluated site as well as the time (and therefore costs) implied in the remediation of the site. Finally, there are several KO-criteria regarding the properties of each individual site that will determine whether a group of technologies is suitable for implementing for the remediation of the site. These criteria correspond to the soil's clay content, permeability and organic content, as it may be observed in Table 44.

Table 44. KO-Criteria for the determination of the suitability of remedial technologies

Technology group	Method	KO - Criteria		
		max. Clay fraction [%]	min. kf - Value [m/s]	max. Organic content [%]
Microbiological process	BVE	35	1.00E-04	100
	COM	35	1.00E-08	100
Thermal process	INC	35	1.00E-20	100
Physico-chemical process	SWA	30	1.00E-20	15
	SAE	-	1.00E-06	100
Landfilling	BOD	100	1.00E-20	2
	CBAU	100	1.00E-20	3
	RES	100	1.00E-20	3
	MAS	100	1.00E-20	5
Containment	UMS	100	1.00E-05	100
	SLI	100	1.00E-05	100
	SMA	100	1.00E-05	100

Considering the collected data for technical suitability according to the pollution characteristics, the type of soil at the site, and limit values to be achieved for the remediation of the site, a selection of the possible remedial measures for the management of the site is made. An analogue procedure has been followed regarding the management of polluted groundwater, where further fuzzy sets have been obtained.

4.2.2.2 Determination of possible process combinations and evaluation of performance and associated project costs

After the suitability of the remedial technologies has been established, it is then suggested to perform a combination of the suitable technologies. This procedure is largely utilized in order to reduce treatment costs and in the case of a heterogen pollution distribution. This process combination can only be performed once the individual technologies have been evaluated.

Once the suitable technologies and their combinations have been determined, an important step is the calculus of the associated remediation costs. Table 45 presents the actual costs of each of the technological alternatives evaluated in this system (derived from the Austrian experience in contaminated sites management)[1].

Table 45. Specific costs for the different remedial technologies

Remedial alternative	Accronym	Specific costs	Units
Excavation & triage		38	EUR/t
Landfilling	MAS	48	EUR/t
	BAU	22	EUR/t
	RES	97	EUR/t
Thermal treatment	INC [(a)]	160	EUR/t
	INC [(b)]	350	EUR/t
	TDE	230	EUR/t
Solidification	SOL	85	EUR/t
Biological treatment	COM	70	EUR/t
	BVE	150	EUR/t
Soil washing	SWA	130	EUR/t
Surface cover	CAP	70	EUR/m²
		0.02	EUR/m²/year
Vertical containment	UMS	125	EUR/m²
	SMA	50	EUR/m²
	SLI	250	EUR/m²
	SLI	125	EUR/m²

(a) Incineration of non-hazardous wastes, (b) Incineration of hazardous wastes

The results of this evaluation should be provided to all stakeholders involved in the project in order to identify the technologies which, due to limited budgets and financial constrains, should not be further evaluated.

4.2.2.3 Establishment of the budget constrains, as a "knock-out criteria" for the selection of a remedial alternative

As mentioned in the previous section, the last "knock-out criteria" for the determination of the applicability of a technology or remedial action is the interim evaluation from the associated stakeholders involved in the remedial actions. Through this evaluation it is then possible to determine a hierarchy of the proposed technologies, as the stakeholders will commence to provide their elicitations of the suitable remedial alternatives. In this regard, the establishment of restrictions to the budget would imply the preference of the temporal containment technologies over the restoration techologies, waiting for a change in the funding conditions for restoration projects. However, this situation is completely different in each case, so it can only be evaluated with the cooperation of all stakeholders of the project.

[1] Dr. Michael Zorzi, Bundesaltlastensanierungsgesellschaft, Vienna. Personal communication.

The suitable technologies for soil and groundwater remediation/containment selected in this step are subjected to a further evaluation process presented in chapter 4.3.

4.3 Module for the evaluation of feasible technologies and identification of the most appropriate remediation alternative

The development of this module represents the final part of the knowledge-based tool for contaminated sites management. As mentioned in chapter 3.4, this module has been constructed by following a logical framework approach (LFA) to establish a Balanced Scorecard, which is the tool that compares the identified suitable technologies on the basis of the stakeholders' preferences. The procedure described in the following sections deals with the evaluation of suitable technological alternatives, and the final selection of the remedial option that fits to the technical, social and economic parameters imposed by the decision makers or stakeholders involved in the project.

4.3.1 Stakeholders analysis

As result of the stakeholder analysis, the most occurrent organizations/individuals taking part in a remediation project have been identified as follows (see Figure 61). The identification of their interests is an important aspect for the determination of the associated weights of the objectives incorporated to the Balanced Scorecard, as it will be shown in chapter 4.3.4. Figure 61 presents the simplified relationships among these selected stakeholders.

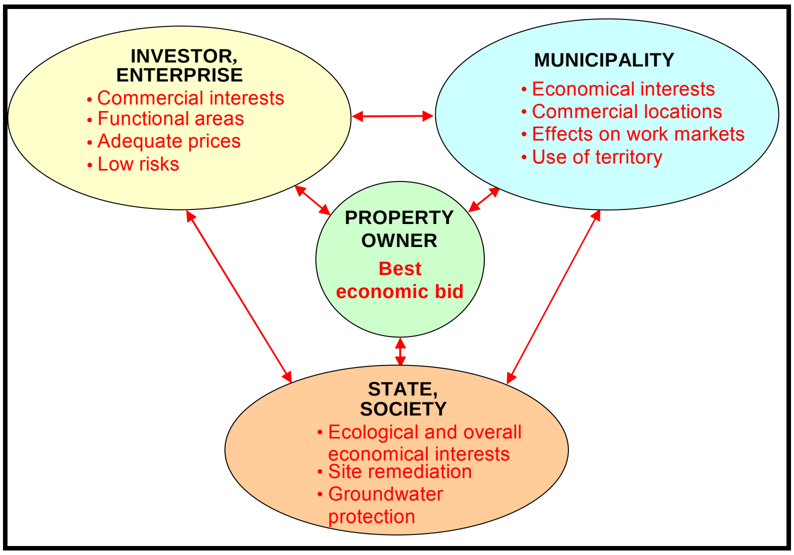


Figure 61. Most common participants in a contaminated sites remedial project [144]

- The **property owner**, who aims at marketing of the surface on optimum conditions and thus at a price as high as possible. Its interests are not necessarily bound to the reuse of the location or real estate.
- The **investor** has the priority of establishing a functional building or enterprise on a favorable location, considering economical interests (e.g. prices low as possible, reuse of

real estate with profits as high as possible). However, no additional unforeseen risk from its previous use should be taken over.

- The **municipalities** pursue surface recycling projects with priority economic interests such as operating settlement, the utilization of positive job effects and income increases. Further efforts are made towards a homogeneous regional/local development as well as the protection of the local landscape and environment, and the minimization of disaggregation costs.
- The **State** interests predominantly lie in the overall economic as well as ecological range. For this goal, targets for the site remediation, groundwater protection and measures for securing the order as well as the reduction of green areas consumption are created.

4.3.2 Problem and objective analysis

The main purpose of the problem analysis is to create a better understanding of the decision problem. An integral decision-making strategy for selecting the most suitable remedial option for contaminated sites should consider all technical requirements as well as the objectives provided by all decision makers that are involved in remediation projects. By combining these priorities with technical requirements, it has been possible to obtain a structure of objectives (Table 46) to follow for evaluating remedial options for contaminated sites [20],[144],[47]. From the developed definitions, the objective tree can already be organized. Figure 62 is the representation of casual relationships between all objectives of the project, illustrated by an objective tree.

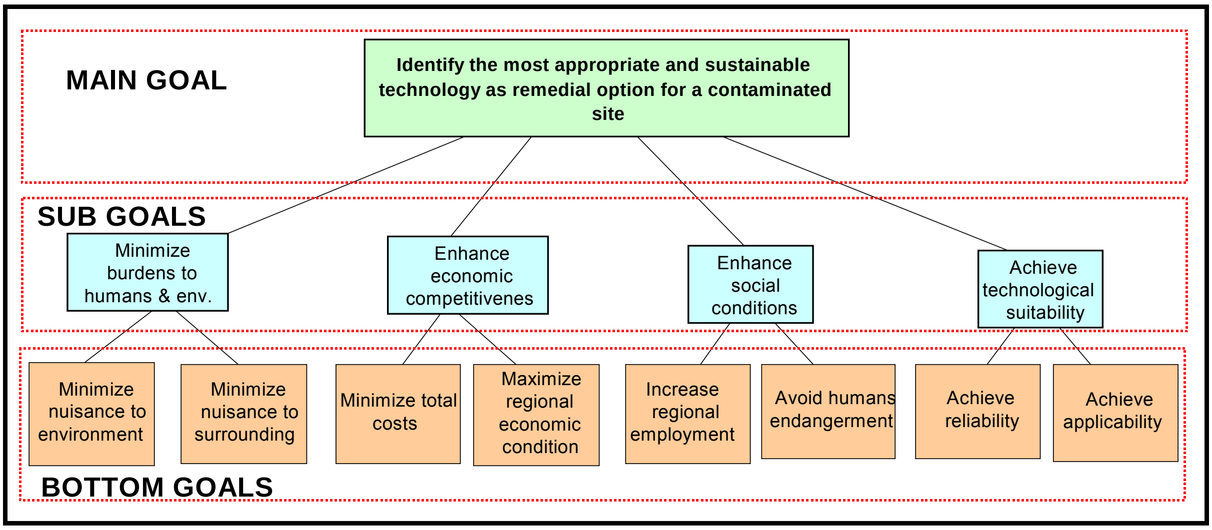


Figure 62. Objective tree for the selection of the most suitable technology for site remediation.

Table 46. Definition of goals and sub-goals of the goal tree for the Balanced Scorecard.

Objective / Subgoals	Description / Definition
Main Goal: Identify the most appropriate and sustainable technology for site remediation	To identify and select the most appropriate technology for the remediation of contaminated soil and/or groundwater, based on technical, economic, social, legal and regional conditions or points of view.
1. Minimize impacts to humans and environment	To pursue the minimization of the impacts associated to the implementation of a technology for the remediation of a contaminated site.
1.1. Minimize nuisance to surroundings	To minimize the nuisance (e.g. noise, transport, odour and gas emissions) to neighbours of the contaminated area.
1.2. Minimize environmental burden	To minimize the burden to the environment (i.e. energy consumption, waste generation) that is associated to a remediation technology for soil and/or groundwater.
2. Enhance economic competitiveness	To maximize the enhancement of the economic conditions of the project by providing the best investment scenario.
2.1. Minimize total costs	To minimize the costs associated to the remediation activities, both in investment and in operation.
2.2. Maximize regional economic condition	To maximize the economic condition of the region surrounding the contaminated area during and after the restoration activities.
2.2.1 Max. use of local resources	To maximize the use of local resources during the restoration activities.
2.2.2. Increase value of surrounding land	To maximize the enhancement of the land value of the properties surrounding the contaminated area.
3. Enhance social conditions	To optimize the conditions of the inhabitants of the area where the restoration activities take place.
3.1. Increase regional employment	To maximize the use of local manpower in the restoration activities.
3.2. Avoid humans endangerment	To ensure the minimization of the risk associated to the pollutants, and its influence on the human health in a long term basis.
4. Achieve technological suitability	To maximize the suitability of the selected technology in a regional basis, by ensuring its availability in the local vicinity as well as its performance in similar conditions to the ones of the present project.
4.1. Achieve reliability	To ensure that a number of remediation projects already have been carried out with the evaluated technology to restore the site in similar conditions to the ones present in the evaluated case.
4.2. Achieve availability	To ensure and to prefer the availability in the local region for the needed technological supplies for the restoration activities.

4.3.3 Definition of indicators and utility functions for the evaluation of remedial options for contaminated sites

As mentioned in chapter 2.6.2, the selection of indicators is made naturally from the objective tree. For the case of indicators selection for the Balanced Scorecard for contaminated sites technologies evaluation, a set of 11 indicators have been identified, which are introduced in Table 47. Figure 63 shows the relationship between objectives and the respective selected indicators.

Table 47. Definition of indicators for evaluating soil and groundwater remedial options.

ID	Indicator name	Units	Supported Sub-goal	Provided by
I01	Environmental burden of the technology used	dml [a]	1.1	BP
I02	Total associated costs	cu	2.1.	TA
I03	Local resources used during restoration	%	2.2.1.	EUS
I04	Size of influenced region	ha	2.2.2.	EUS
I05	Increase of land value	%	2.2.2.	EUS
I06	Nuisance to human environment	dml [a]	1.1.	BP
I07	Number of employed people in restoration	mh/Mg	3.2.	TA
I08	Risk of pollutants to the human health in a long term.	%	3.3.	TA
I09	Number of demonstration projects using the selected technology for the addressed pollutants	dml	4.1.	BP
I10	Percentage of supplies that can be acquired locally for the evaluated remediation technology	%	4.2.	EUS
I11	Local technology level for supporting maintenance	dml [a]	4.2	EUS

dml: Dimensionless; cu: Currency units; ha: Hectares; mh: Man hours; BP: Results of the benchmarking process of technologies for soil and groundwater remediation; TA: Technical assessment and evaluation; EUS End user.
[a] Each technology has been provided with a characteristic value in a scale from 1 to 10, according to the results of the benchmarking process.

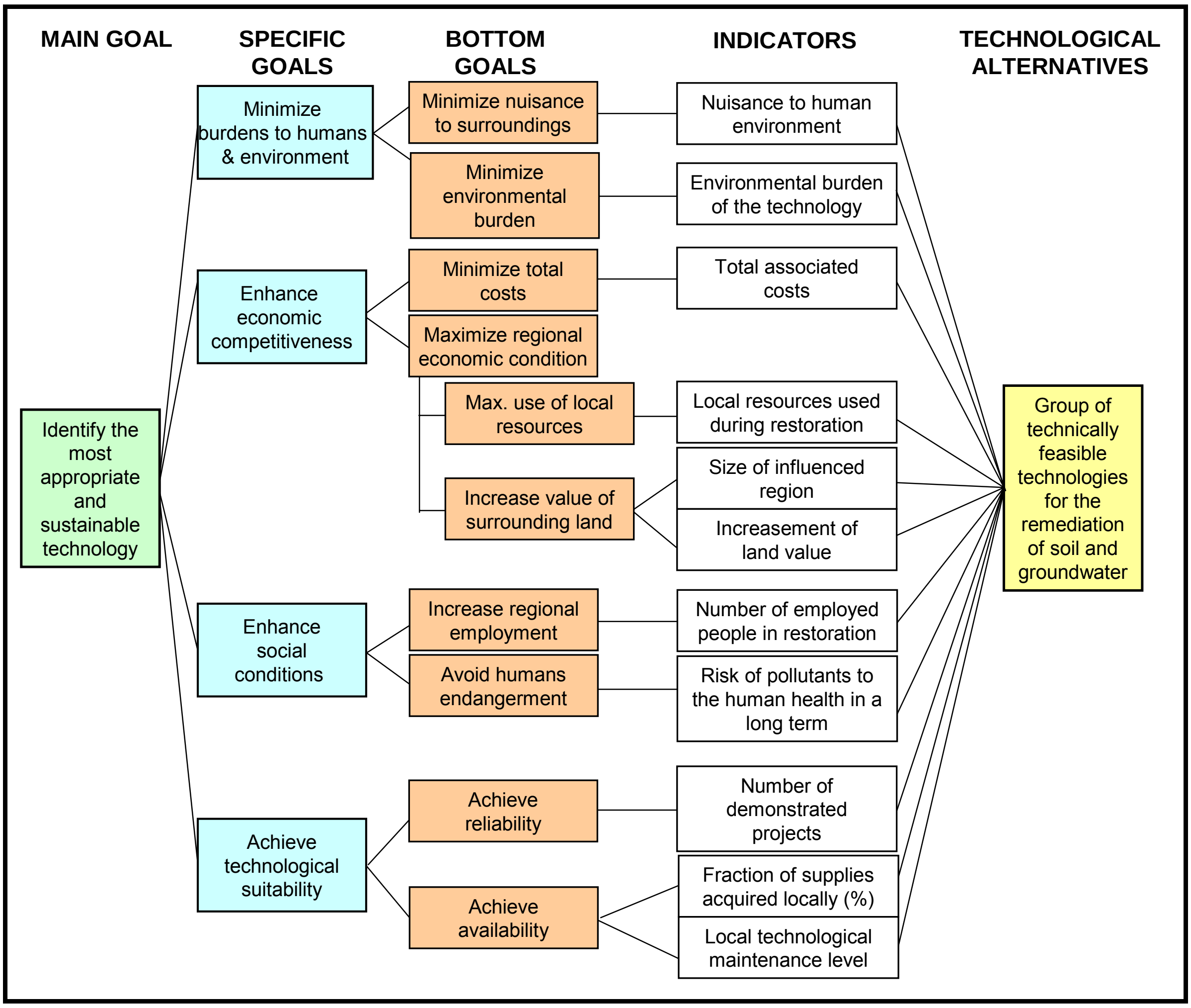


Figure 63. Overview of the objective tree and selected indicators for the implementation of the Balanced Scorecard (BSC).

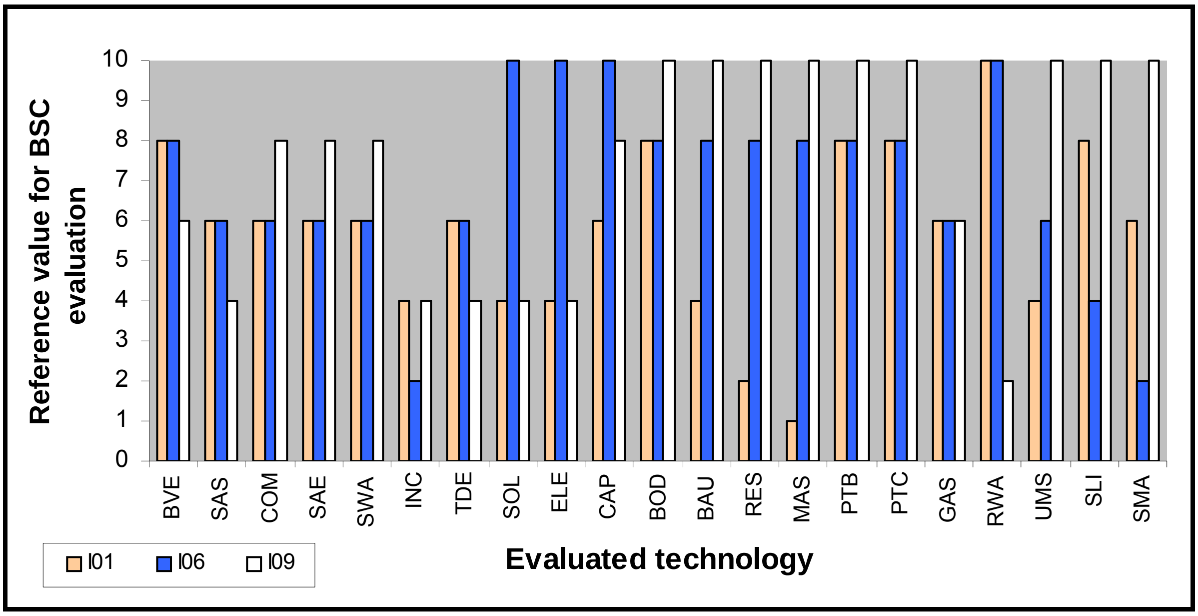


Figure 64. Results of the benchmarking evaluation for the groundwater and soil remediation technologies used as fixed values for selected BSC indicators.

As it may be observed in Table 47, there are three sources for the determination of the indicators value. First, there is the end user being responsible for the indicators I03, I04, I05, I10, I11. A second source is the technological evaluation, as described in chapter 4.2, which provides the information required for indicators I02, I07 and I08. For the remaining indicators, their values have been determined through a benchmarking evaluation process.

From this comparative evaluation, the values for the indicators I01, I06 and I09 have been fixed for each addressed technology (chapter 3.3.2), and are presented in Figure 64, page 120. For the indicators whose value should be entered by the end user, a series of attribute functions have been prepared in order to offer a simple but robust evaluation, as seen in Figure 65. Please note that for the determination of the attribute value of sub-goal 2.2.2. (Table 49), the value for the indicator I05 must be first determined through Table 48.

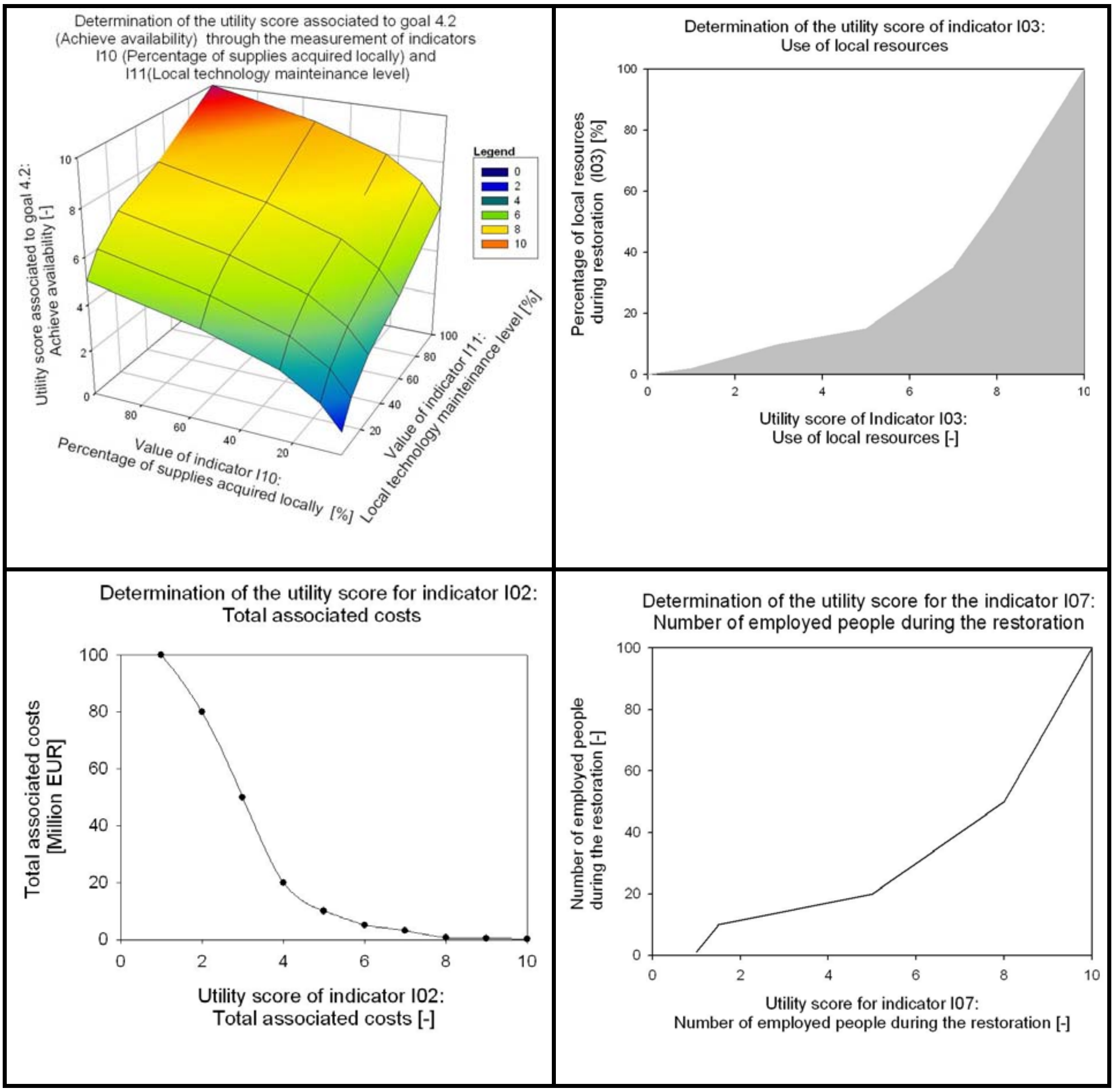


Figure 65. Attribute functions for values for the different goals and indicators in the BSC.

Table 48. Determination of the scores for I05.

Current soil use	Possible soil use after remedial project using selected technology				
	Not suitable for use	Industrial activities	Agricultural activities	Recreational areas	Habitational areas
Not suitable for use	1	3	6	9	10
Industrial activities	-	1	5	7	9
Agricultural activities	-	-	1	6	7
Recreational areas	-	-	-	1	5
Habitational areas	-	-	-	-	1

Table 49. Determination of the attribute value for sub-goal 2.2.2.

Size of influenced region (score of I04)	Score of I05 (derived from Table 48)				
	1-2	3-4	5-6	7-8	9-10
Local (changes only inside of property)	1	2	3	4	5
Small (changes for direct neighbor properties)	2	3	4	5	6
Medium (changes for neighborhood)	3	4	5	6	7
Large (changes for city level)	4	5	6	7	8
Regional (changes influence over city level)	6	7	8	9	10

It has been already mentioned in chapter3.4.1.1, that both continuous and discrete utility functions have been used for determining the utility value of the bottom goals. In the present work, it has been determined that the scale to be utilized for the characterization of the envisaged attributes should be from 1 to 10, being 10 the best value to be achieved. The selected continuous utility functions (following the same key presented in eq. (11), chapter 3.4.1.1) for determining the values of the different goals are presented in equations (14) and (15), which represent the functions for objectives to be maximized and minimized, respectively [230]. A third continuous function, presented in eq. (16), has been determined suitable for the calculus of the utility value in the case of the costs comparisons, as it brings the implication of budget constrains to the elicitation of the sub-goal [216]. Considering the utility functions presented in equations (14)-(16), Table 50 presents the quantitative problem formulation associated to each goal.

(Maximize function)

$$U(A_i) = \left(\frac{c_j(A_i) - c_{\min}}{c_{\max} - c_{\min}} \right) \cdot 10 \quad (14)$$

(Minimize function)

$$U(A_i) = \left(\frac{c_{\max} - c_j(A_i)}{c_{\max} - c_{\min}} \right) \cdot 10 \quad (15)$$

(Minimize costs function)

$$U(Cost_i) = 10 \cdot \sqrt{1 - \frac{Cost_i^2}{Cost_{\max}^2}} \quad (16)$$

Table 50. Definition of the problem formulation for all goals of the Balanced Scorecard (BSC)

Subgoal	Problem formulation	Defined in eq.
1.1. Minimize nuisance to surroundings	Minimize $\sum U(A_i)$	(15)
1.2. Minimize environmental burden	Minimize $\sum U(A_i)$	(15)
2.1. Minimize total costs	Minimize $\sum U(Cost_i)$	(16)
2.2. Maximize regional economic condition	-	-
2.2.1 Max. use of local resources	Maximize $\sum U(A_i)$	(14)
2.2.2. Increase value of surrounding land	Maximize $\sum U(A_i)$	(14)
3.1. Increase regional employment	Maximize $\sum U(A_i)$	(14)
3.2. Avoid humans endangerment	Minimize $\sum U(A_i)$	(15)
4.1. Achieve reliability	Maximize $\sum U(A_i)$	(14)
4.2. Achieve availability	Maximize $\sum U(A_i)$	(14)

4.3.4 Development of the Balanced Score Card for the selection of the best available suitable technology for contaminated sites

The final step for the construction of the Balanced Scorecard is the weighting of the goals by the decision-makers. For this purpose, as mentioned in chapter 3.4.1.1, two methods have been applied, namely the Analytic Hierarchy Process (AHP) and the Simple Multiattribute Rating Technique (SMART) processes. The AHP process has been used for the weighting of the first level of sub-goals whilst the SMART process supports the weighting of the bottom goals of the BSC. Through the application of both processes the points of view of the three stakeholders defined in chapter 4.3.1 have been considered. In order to provide a simple tool, all features of the proposed BSC have been built in MS Excel®. Whereas this tool is intended to be used by experts in contaminated sites remediation, the system has been left open for decision-makers to introduce their preferences to weight the different goals for the remediation project. The resulting weights of sub-goals according to the possible decision makers are presented as follows.

The weighting of the first level sub-goals has been performed by using both elicitation processes, for comparison purposes (Table 51 and Table 52). It may be observed that both elicitation processes provide similar weights, although this fact may change when a different scale is used for determining the relative importance of the goals (in this case, a 1-to-5 scale has been used). This situation will be further analyzed in the sensitivity analysis, chapter 4.3.5. The elicitation process is made for each stakeholder of the project. After all weights are calculated, the stakeholders must follow the procedure described in chapter 4.3.3 for establishing the scores for each bottom goal of the objective tree. Once all stakeholders have provided their individual and subjective elicitation preferences, it is the responsibility of the project manager and the decision process analyst to generate integrated, consented weight scores, which takes into consideration all preferences from all stakeholders, bringing them together into one weighting system.

Table 51. Weights elicitation for the first level sub-goals using the AHP method.

1.- Weighting of goals according to S1

	Goal 1	Goal 2	Goal 3	Goal 4	*wj*
Goal 1	1		1.5	2	0.220
Goal 2	3	1	3	5	0.585
Goal 3			1	2	0.146
Goal 4				1	0.049

2.- Weighting of goals according to S2

	Goal 1	Goal 2	Goal 3	Goal 4	*wj*
Goal 1	1		1.5		0.192
Goal 2	1.5	1	1.5	1	0.385
Goal 3			1		0.077
Goal 4	1.5		2	1	0.346

3.- Weighting of goals according to S3

	Goal 1	Goal 2	Goal 3	Goal 4	*wj*
Goal 1	1	2	1	2	0.480
Goal 2		1		1.5	0.200
Goal 3		2	1		0.240
Goal 4				1	0.080

Legend:

Goal 1: Minimize burden to humans and environment
Goal 2: Enhance economic competitiveness
Goal 3: Enhance social conditions
Goal 4: Achieve technological suitability

Table 52. Calculation of Level 2 sub-goals weights according to all defined stakeholders for the site remediation project using the SMART process.

ID Goal	Objective / Subgoals	Level 2 bottom goals elicitation			Level 2 goals relative weights [%]			Level 2 goals absolute weights [-]		
		S1	S2	S3	S1	S2	S3	S1	S2	S3
G1.1.	Minimize nuisance to surroundings	3	2.5	4	46.2	45.5	44.4	0.10	0.09	0.21
G1.2.	Minimize environmental burden	3.5	3	5	56.8	54.5	55.6	0.12	0.10	0.27
G2.1.	Minimize total costs	5	3.5	2	58.1	70.0	30.8	0.34	0.27	0.06
G2.2.	Maximize regional economic condition	3.5	1.5	4.5	41.2	30.0	69.2	0.24	0.12	0.14
G3.1.	Increase regional employment	1.5	3	4.5	23.1	42.9	52.9	0.03	0.03	0.13
G3.2.	Avoid humans endangerment	5	4	4	76.9	57.1	47.1	0.11	0.04	0.11
G4.1.	Achieve reliability	4	4	5	72.7	57.1	50.0	0.04	0.20	0.04
G4.2.	Achieve availability	1.5	3	5	27.3	42.9	50.0	0.01	0.15	0.04

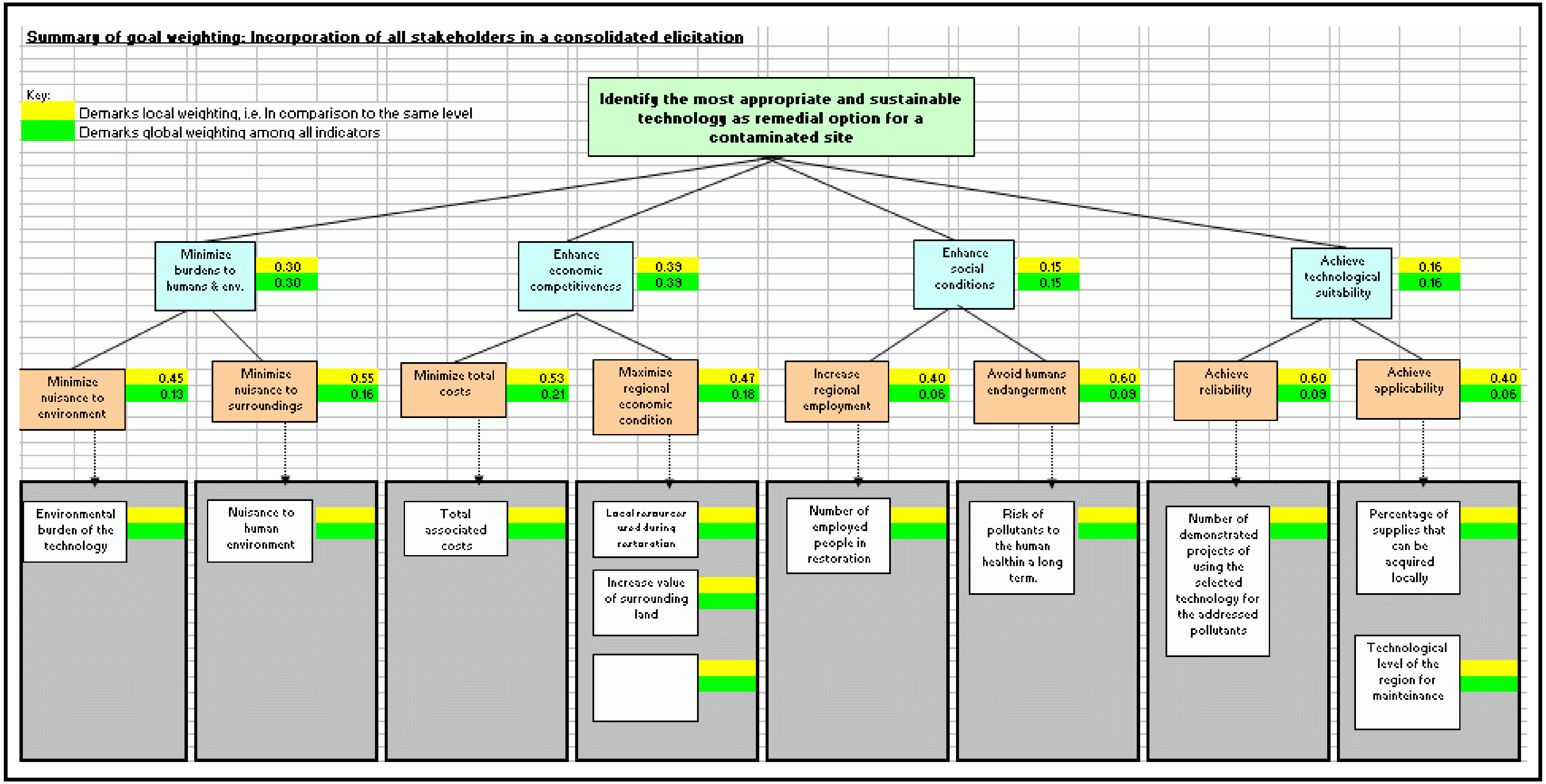


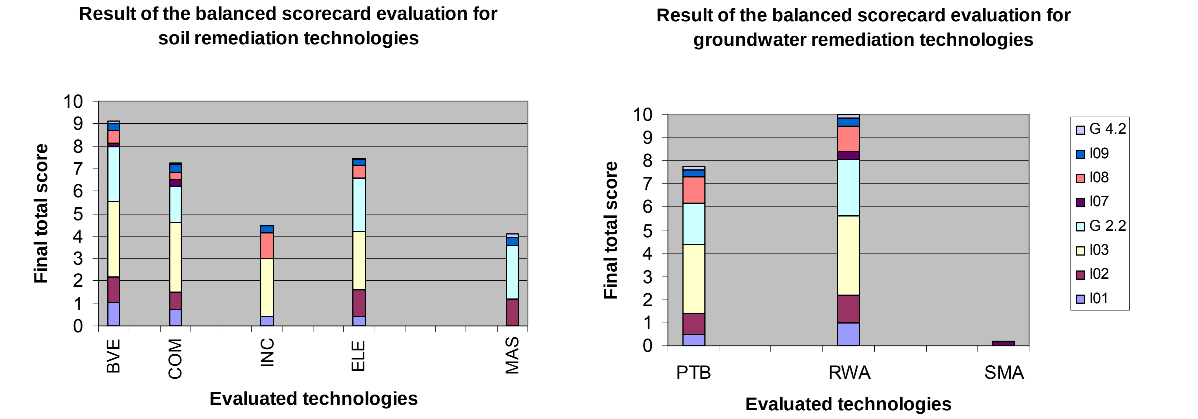
Figure 66. Scheme of the relative weights resulting for all goals in the objective tree, according to the integrated elicitation of all stakeholders

Figure 66 presents the weighted goal system for the introduced example. It can be observed that the goals have a relative as well as an overall weight in the goal system. The values obtained in Table 51 represent the weights in a local consideration. When established into the goal system, those weights will comprehend a definitive global value as shown in Figure 66. The example at hand deals with the hypothetical case of a property in which mostly organic pollutants have been found, and where bioventing, ex-situ composting, incineration, electrochemical remediation and deposition in a class 4 landfill have been found suitable for remediating the soil media. Moreover, "pump and treat" with biological treatment, reactive walls with a funnel-and-reactor approach and containment by sheet piles have been found suitable for managing the contaminated groundwater. Table 53 presents the results for the determination of the scores of each bottom value. The shown scores present already the maximization and minimization processes described in chapter 4.3.3.

Table 53. Results of the evaluation on the indicators for the selected technologies presented as scores of their associated bottom goals.

Technology	G1.1	G1.2	G2.1	G2.2	G3.1	G3.2	G4.1	G4.2
BVE	10.0	10.0	9.7	10.0	5.0	5.0	9.7	7.5
COM	7.1	6.7	9.0	6.7	10.0	2.5	10.0	5.0
INC	4.3	0.0	7.5	0.0	0.0	10.0	9.7	0.0
ELE	4.3	10.0	7.5	10.0	0.0	5.0	7.5	2.5
MAS	0.0	10.0	0.0	10.0	0.0	0.0	10.0	10.0
PTB	5.0	7.5	8.7	7.5	0.0	10.0	8.7	10.0
RWA	10.0	10.0	10.0	10.0	10.0	10.0	10.0	8.3
SMA	0.0	0.0	0.0	0.0	6.0	0.0	0.0	0.0

The system then takes the obtained scores into a second calculation matrix where the elicitated weights are considered for the determination of the relative scores of the bottom goals into the Balanced Scorecard. The results of the weighted process are presented in Figure 67, page 127. From the results it is evident that the use of bioventing (BVE) for the remediation of the contaminated soil has been selected as the most appropriate solution for the site. A major contribution to this solution was the reliability of the technology to remediate organic-contaminated soils, the type of technology (i.e. in-situ decontamination measure), which avoids a high heavy-load traffic in the vicinity of the area, and the fact that in this case time is not a limiting factor and therefore the duration of the remediation process has not been considering as an obstacle for the selection of the technology, as the lower remediation costs should compensate such a variable. For managing the contaminated groundwater the funnel and reactor approach has been selected over the pump and treat process. Although less reliable in terms of demonstrated projects, the use of a passive remedial option has been found as a sound alternative for this case.



LEGEND: BVE: in-situ Bioventing, COM: off-site Composting, INC: off-site Incineration, ELE: Electrokinetic stabilization, MAS: Mass-rest landfill, PTB: on-site Pump&Treat + Bioremediation, RWA: Reactive Walls, SMA: Thin cut-off wall. I01:Environmental burden of the technology used, I02:Total associated costs, I03:Local resources used during restoration, I04:Size of influenced region, I05:Increase of land value, I06:Nuisance to human environment, I07:Number of employed people in restoration, I08:Risk of pollutants to the human health in a long term, I09:Number of demonstration projects using the selected technology for the addressed pollutants, I10:Percentage of supplies that can be acquired locally for the evaluated remediation technology, I11:Local technology level for supporting maintenance. G2.2 and G4.2 correspond to the scores calculated from I04, I05 and I06, and from I10 and I11, respectively.

Figure 67. Exemplary results of the weighted evaluation for the selected technologies.

4.3.5 Sensitivity analysis for the developed Balanced Scorecard

The sensitivity analysis intends to provide the stability of the Balanced Scorecard System regarding changes in the elicitation procedure. As described in chapter 4.3.3, the sensitivity analysis consisted in the variation of each individual goal weight to determine the influence on the final evaluation. For this reason, the weights were given three sets of elicitation values, namely the real value, as well as a zero-importance and a maximun-importance values (i.e., $p_i = 0$ and $p_i = 5$, with p_i defined in eq. (12). The results of the performed sensitivity analysis are presented in Figure 68. It can be observed that the modification of the different values of importance for each goal of the system affects the end technology evaluation. Nevertheless, only the importance variation of Goals 2.1, 2.2 and 3.2 show a significant influence on the final results of all evaluated technologies. A special attention shall be therefore made during the elicitation process to the goals that deal with social and economic aspects, basis for the performed sensitivity analysis.

As an outlook for this activity, it is intended to perform the sensitivity analysis to the scale utilized for the elicitation of the goals importance. Instead of evaluating the scale's value ranges, it is far more interesting to determine the sensibility of the system regarding the introduction of a more or less continuous elicitation scale. That is, to evaluate the effects of the introduction of a more discrete or a more continuous elicitation scheme on the final result.

A further sensitivity analysis consists on the determination of possible scenarios in which the stakeholders may slightly vary their elicitation. That is, to study the effects of changes in the conditions of the contaminated site or its surroundings onto the system. Especially interesting in this case is the study of the sites which have been categorized at the limit of a priority class, in order to determine the effects (i.e., "what if"?) of a changing condition onto their priority level and/or established mechanisms for remediation.

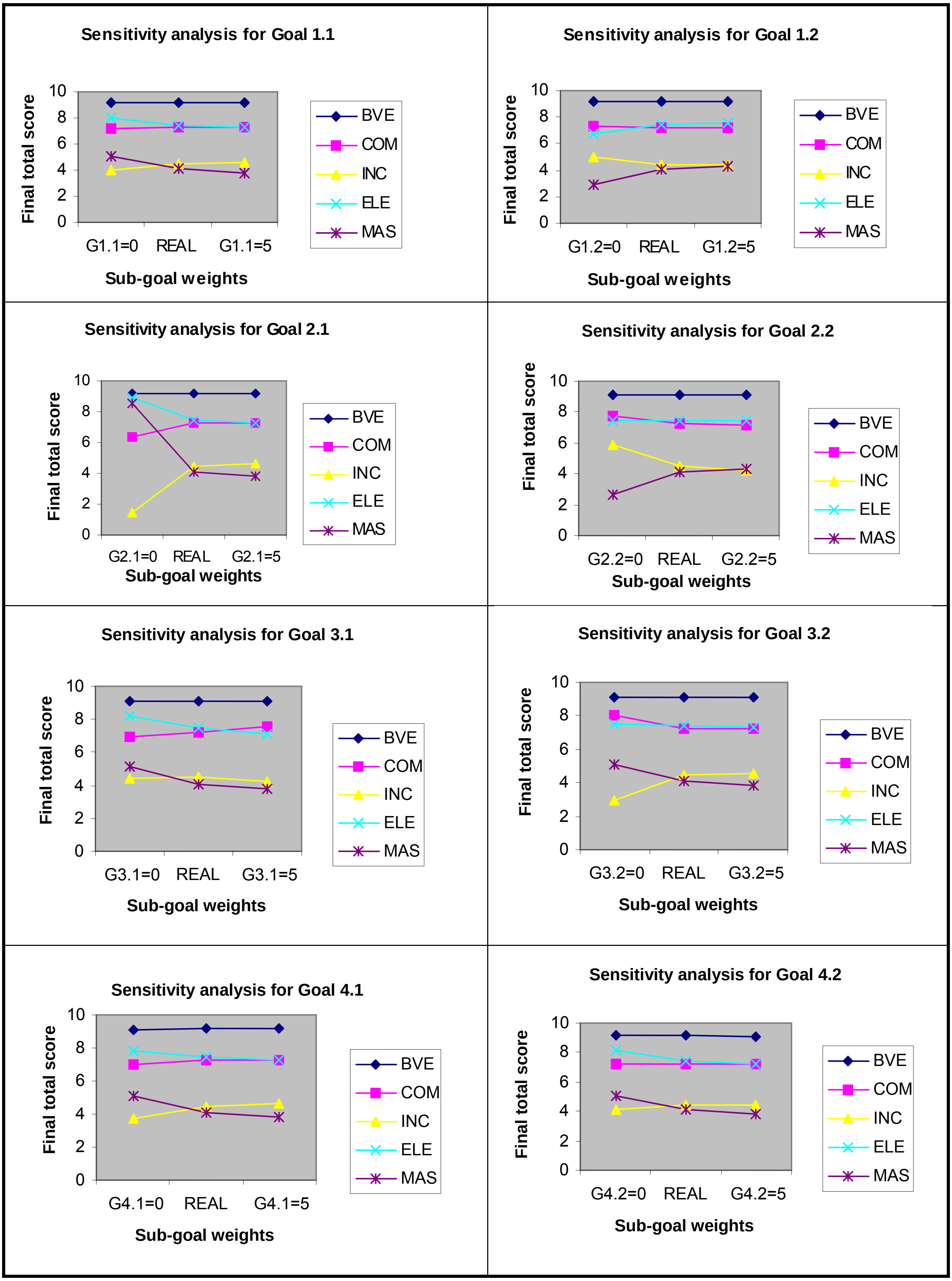


Figure 68. Results of the performed sensitivity analysis.

4.4 Model validation by case study

As for all developed methods, an important aspect to consider is the validation process for the proposed model. In this case, one site management example from the Austrian experience has been selected. This section aims to check the developed toolset in its foundation and application against the already mentioned study case, which stand as an important remediation example at an Austrian national level. The site description is provided in detail in Annex VIII.

4.4.1 Results of the evaluation using the developed system

The following sections introduce the procedure for identifying technical remedial alternatives for the management of the study case site.

4.4.1.1 First risk assessment

Inputs:

Industrial activity: Petroleum refinery
Extension: 180,000 m²
Present pollutants: Mineral oil

Calculus:
The industrial activity has associated values of material danger and probability of occurrence as follows:

S_0 = 5 (Petroleum refinery)
P = high (associated probability of occurrence)
f(P) = 1.1

Extension (> 5 ha) : Large
f(extension) = 1.2

f(G) = 1.5 (Individual and/or local water supplies)
f(S) = 1.7 (In urban areas without possibility of direct contact to children)
f(N) = 1.3

$$f(Env.Goods) = 1 + \frac{f(G) + f(S) + f(N) - 3}{10} = 1.15$$

$$R_{1stRA} = [S_0 \cdot f(P)] \cdot f(Extension) \cdot f(Env.Goods)$$

$$R_{1stRA} = [5 \times 1.1] \times 1.2 \times 1.15 = 7.6$$

According to the first risk assessment evaluation, this site is classified as **Priority B**, and therefore it should be further evaluated in the secod risk assessment, which is presented in the coming section.

4.4.1.2 Second risk assessment

The second risk evaluation brings an interesting result. For this site, the evaluation classifies the study case as Class B, although having a R value of 8.0. This situation is due to the proximity of the result (R = 7.95) to the limit value between the Class A and Class B. In this case, this site has been considered as Class A.

Table 54. Summary of results for the second risk assessment procedure

N°	Code	S-Value	f(Extension)	V-Value	N-Value	H-Value
1	Validation	9	1.2	7	6.5	7.5
		R	Priority			
		8.0	B			

4.4.1.3 Identification of feasible technologies for the study case remediation

<u>Inputs:</u>

Industrial activity: Petroleum refinery
Extension: 180,000 m²
Present pollutants: Mineral oil

Hydrogeological conditions:

Soil permeability = $8.9 \times 10^{-7} – 7.4 \times 10^{-6}$ [m/s]
Soil organic content: Low
Groundwater layer depth: 10m
Groundwater flow: 0.1 – 0.5 m/d

<u>Calculus:</u>

a) Determination of adequate conditions for in-situ measures

For this step, the evaluation of the volatility and solubility of the present contamination is determined. Figure 69 shows the results of this evaluation. The results of this calculus show that the pollution is characterized by a fair solubility and volatility. Since it is dealt purely with hydrocarbons, the degradability of the mixture of pollutants is also considered adequate for in-situ measures. However, the presence of a highly compacted central area makes the application of in-situ biological measures in this zone unpracticable (as determined in Table 10, page 50).

Figure 69. Determination of the volatility and solubility of the present pollutants according to their physico-chemical properties and the soil conditions.

b) Determination of the technical suitability of remedial options

The second step consists on determining the technical feasibility of applying the remedial technologies in terms of their active principle. Therefore, at this point the suitability of physico-chemical, thermal and bioedegradation measures are evaluated. From Figure 70 it is possible to observe that all groups of ex-situ technologies are suitable for this project. When compared against the knock-out criteria for remedial technologies (Table 48, page 123), it is possible to observe that the site conditions do not fall after any restriction (clay fraction, permeability, organic content), and therefore the application of all technologies assessed in this evaluation is feasible, with exception of in-situ biological measures as mentioned in the previous section. Nevertheless, the evaluation provides already with a hierarchy for the evaluated technologies, which is presented as follows with the resulting scores of the evaluated technologies.

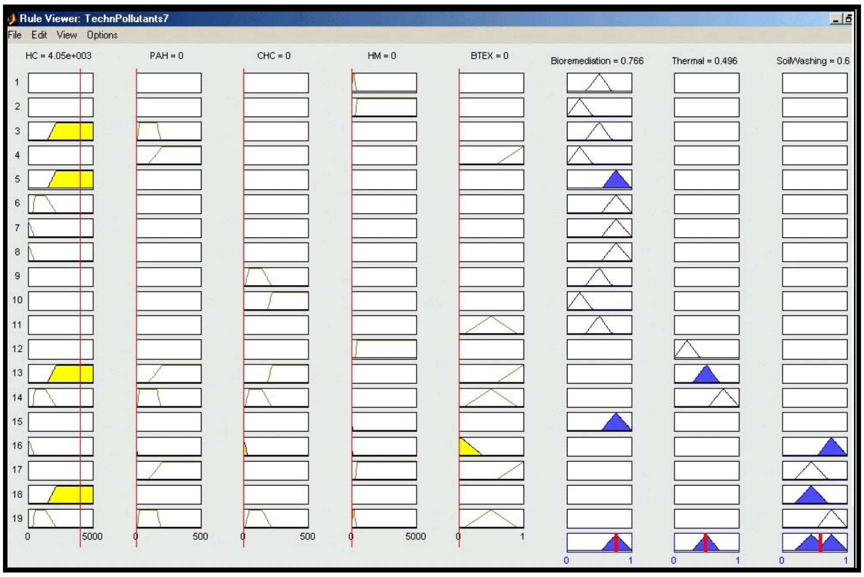


Figure 70. Evaluation of the technical suitability of the remedial option groups according to the present contamination.

c) Determination of the technical suitability of containment options

The third step consists in the determination of the feasible containment technique applicable to use under the specific site conditions. For this evaluation, Table 10 (page 42) are utilized as the basis of comparison. It can be observed that all containment techniques are suitable for securing the study case site. However, it is also possible to observe that under the conditions of the site the sheet piles have two big advantages, namely cheaper costs and the possibility to retire them after remediation.

d) Determination of process combinations

Besides considering soil remediation technologies as individual alternatives, it is possible to distinguish the following process combinations for this study case site:

Table 55. Description of the identified processes for implementing at the study case site.

Techn. ID	Process / Process combination	Description
ALT1	SWA	Excavation and soil washing of the total contaminated mass
ALT2	INC (dang.)	Excavation and incineration of the total contaminated mass
ALT3	RES	Excavation and landfilling of the total contaminated mass
ALT4	UMS	Total containment of the property and implementation of
ALT5	SLI COM SWA	Containment of central area through temporal cut-off wall, composting of aquifer in the periphery area, soil washing of cover layer from periphery area, soil washing of central area
ALT6	SLI SWA	Containment of central area through temporal cut-off wall, soil washing of total area
ALT7	SLI Excavation RES	Containment of central area through temporal cut-off wall, excavation, triage and disposal in residual-waste landfill
ALT8	SLI INC	Containment of central area through temporal cut-off wall, incineration for dangerous materials

e) Determination of project costs

For the calculus of the project costs, the current prices for the implementation of the state-of-the-art technologies have been obtained. According to these prices, the following costs should be incurred for the various alternatives presented by the evaluation process:

Table 56. Estimation of the total associated costs of the identified suitable technologies for managing the study case site.

Techn. ID	Process / Process combination	Total associated costs [k€]
ALT1	SWA	147,420
ALT2	INC (dang.)	396,900
ALT3	Excavation RES	160,745
ALT4	UMS	1,500
ALT5	SLI COM SWA	117,730
ALT6	SLI SWA	148,080
ALT7	SLI Excavation RES	161,435
ALT8	SLI INC	417,435

From the obtained results, it is possible to discard ALT2 and ALT6 because of their high comparative associated costs. Moreover, ALT1 and ALT3 do not fulfill the conditions of confining the site during the restoration project, which is suggested by the risk assessment procedure. Finally, ALT4 is discarded because it does not imply a reduction of the pollutants inventory whilst the property itself is already in use for industrial activities. The alternatives to be evaluated in the BSC are therefore ALT3, ALT5, ALT6 and ALT7.

4.4.1.4 Utilization of the Balanced Scorecard for the determination of the most appropriate technology to use in the case study

After obtaining the list of possible remedial options for the management of the contaminated site in study, the use of the developed BSC is intended to determine the most appropriate option. As stakeholders preferences the same elicitation process for the Chapter 4.4 has been utilized, since the actual stakeholders from this project have not been reached. The results of the BSC evaluation are presented as follows:

GOAL 1: Minimize burdens to humans & env.

Sub-goal 1.1: Minimize burden on the environment

Indicator: Environmental burden

	0		2.5		5			7.5		10	
Excavation RES									8		8
SLI COM SWA							6				6
SLI SWA								7.5			7.5
SLI Excavation Res									8		8

Sub-goal 1.2: Minimize nuisance to human environment

Indicator: Nuisance to surroundings

	0		2.5		5			7.5		10	
Excavation RES									8		8
SLI COM SWA					5						5
SLI SWA									8		8
SLI Excavation Res									8		8

GOAL 2: Enhance economic competitiveness

Sub-goal 2.1: Minimize total costs

Indicator: Total costs of the restoration technology

	0		2.5		5			7.5		10	
Excavation RES		1.4									1.4
SLI COM SWA		1.6									1.6
SLI SWA		1.4									1.4
SLI Excavation Res		1.4									1.4

Sub-goal 2.2: Maximize regional economic condition

Indicators: Local resources used during restoration & Increase value of surrounding land

	0		2.5		5			7.5		10	
Excavation RES					5						5
SLI COM SWA								8			8
SLI SWA								8			8
SLI Excavation Res					5						5

Sub-goal 3.1: Increase regional employment

Indicator: Number of employed people in restoration

	0		2.5		5			7.5		10	
Excavation RES						6					6
SLI COM SWA								8			8
SLI SWA								8			8
SLI Excavation Res								8			8

Sub-goal 3.2: Avoid humans endangerment

Indicator: Risk of pollutants to the human health in the long term

	0		2.5		5			7.5		10	
Excavation RES						6					6
SLI COM SWA									8		8
SLI SWA										10	10
SLI Excavation Res								7.5			7.5

GOAL 4: Achieve technological suitability

Sub-goal 4.1: Achieve reliability

Indicator: Number of demonstrated projects of using the selected technology for the addressed pollutai

	0		2.5		5			7.5		10	
Excavation RES										10	10
SLI COM SWA								7.5			7.5
SLI SWA										10	10
SLI Excavation Res										10	10

Sub-goal 4.2: Achieve applicability

Indicators: Percentage of supplies that can be acquired locally & Technological level of the region for m

	0		2.5		5			7.5		10	
Excavation RES										10	10
SLI COM SWA										10	10
SLI SWA										10	10
SLI Excavation Res										10	10

The elicitation process results in the following scores:

Summary of scores for all evaluated goals

	G 1.1	G 1.2	G 2.1	G 2.2	G 3.1	G 3.2	G 4.1	G 4.2
Excavatio	10.0	10.0	0.0	0.0	0.0	0.0	10.0	10.0
SLI COM	0.0	0.0	2.1	10.0	10.0	5.0	9.6	10.0
SLI SWA	7.5	10.0	0.0	10.0	10.0	10.0	10.0	10.0
SLI Excav	10.0	10.0	0.0	0.0	10.0	0.0	0.0	0.0

Weighted scores for all evaluated technological alternatives

	G 1.1	G 1.2	G 2.1	G 2.2	G 3.1	G 3.2	G 4.1	G 4.2	Total Score
ALT3	1.0	1.2	0.0	0.0	0.0	0.0	0.4	0.1	2.7
ALT5	0.0	0.0	0.7	2.4	0.3	0.6	0.3	0.1	4.5
ALT6	0.8	1.2	0.0	2.4	0.3	1.1	0.4	0.1	6.3
ALT7	1.0	1.2	0.0	0.0	0.3	0.0	0.0	0.0	2.5

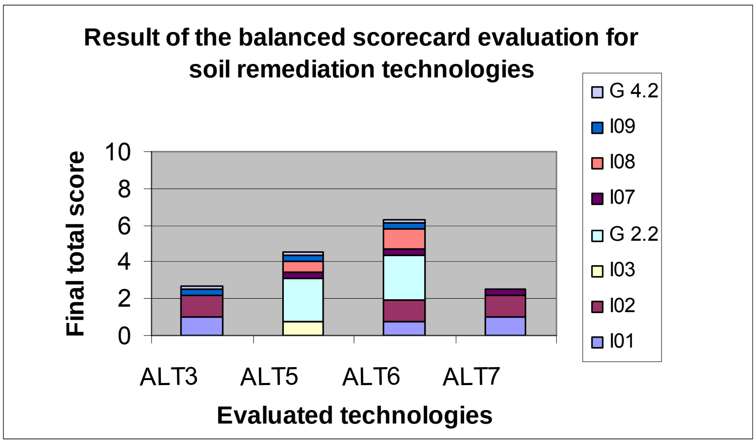


Figure 71. Result of the BSC evaluation for the study case site

It can be observed in Figure 71 that although ALT6 has associated costs ca. 30% higher than ALT5, it represents a much higher score in the overall evaluation. For this study case site it could be then suggested the application of the ALT6 as a management principle. The final decision, however, will be still in hands of the stakeholders, and their financial opportunities for completing the project will be a highly restrictive aspect that has not yet been considered in this evaluation.

4.4.2 Sensitivity analysis of the obtained results

The sensitivity analysis of this model consists on two determinations. First, as already mentioned in Chapter 4.4.1.2, this study case site has been evaluated exactly in the limit of Class A and Class B. For the previous chapter, Class A was selected to perform the study. This first sensitivity assessment will evaluate the technology selection for the site under a priority hierarchy of Class B. The second sensitivity assessment corresponds to the determination of two possible scenarios that can be considered as the “worst case” and “best case” situations. By implementing them it is intended to observe their influence on the obtained results. These scenarios have been defined first by their priority class from the risk assessment procedure, and detailed as shown in Table 57:

Table 57. Definition of scenarios for the sensitivity analysis of the BSC in the case study.

Parameter to be varied	"Real" scenario	Worst-case scenario	Best-case scenario
Calculation of transport costs	For the transport costs a factor of 5% has been included in the total associated costs	20% of the total remediation costs	1% of the total remediation costs
Endangerment class	Class A	Class A	Class B
Nuisance to surroundings	-	Since the case study site is already reused in a further industrial activity, the utility score for the indicator I06 (Nuisance to human environment) has been incremented especially in terms of the time period of the remedial activities and the use of heavy machinery at the site.	If applied in Chile, the national legislative and laboral situation definitevily will allow a less strict acceptance to the nuisance to the surroundings. An enlightened utility score for indicator I06 (Nuisance to human environment) has been implemented for all technologies
Utility scores for indicator I02, total associated costs	-	A new, adapted utility scores function for the indicator I02 has been prepared to better discern among the different evaluated technologies	A new, adapted utility scores function for the indicator I02 has been prepared to better discern among the different evaluated technologies

For the first sensitivity scenario (change of priority class from the risk assessment), from chapter 4.4.1.3 it is possible to determine the technologies that have been found suitable for the management of the case study contaminated site. As in this occasion the site has been categorized under Class B, the restrictions on site containment are not regarded in this evaluation. Therefore, the technological alternatives to be evaluated are as follows:

Table 58. Identified processes for implementing at the study case site.

Techn. ID	Process / Process combination	Total associated costs [k€]
ALT1a	SWA	147,420
ALT2a	COM SWA	117,520
ALT3a	Excavation RES	160,745
ALT5a	SLI COM SWA	117,730
ALT6a	SLI SWA	148,080
ALT7a	SLI Excavation RES	161,435

For the calculation of the sensitivity analysis, the following new utility function for establishing the scores of indicator I02 (Total associated costs) has been developed. This function considers a more "tailor made" approach to the study case.

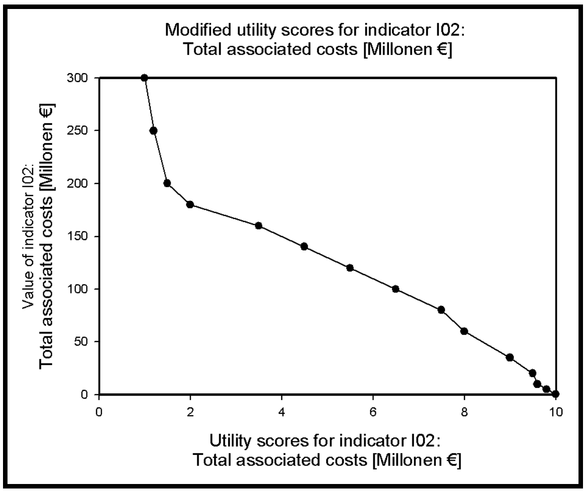


Figure 72. Utility scores of indicator I02, modified for the sensitivity analysis

The results of the sensitivity analysis (Figure 73) coincide in the selection of the process combination Containment/Soil Washing as the most appropriate alternative for the management of the study case contaminated site. By changing the hierarchy class of the contaminated site (i.e., from Class A to Class B), the system has determined a broader spectrum of technically suitable technologies that can be applied at the site; nevertheless, the evaluation in the BSC determines that once again the above mentioned combination of processes is the most suitable alternative to be considered to manage the site.

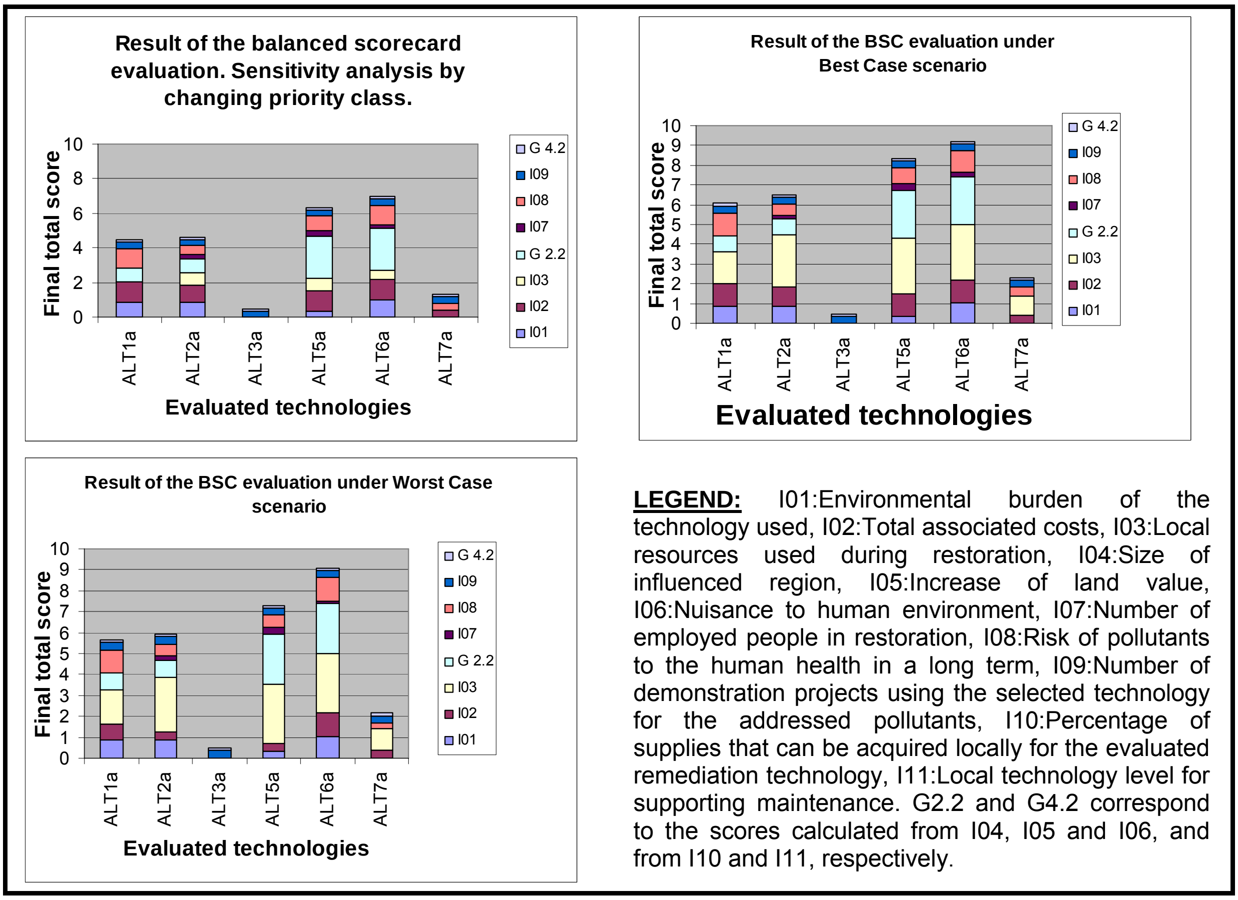


Figure 73. Results of the sensitivity analysis for the case study contaminated site.

The application of the "Best Case" scenario provokes an enhancement on the competitiveness of the technological alternatives. In fact, the alternatives of pure soil washing and Soil Washing/Bioremediation have a rise of almost 50% of their global utility value. Nonetheless the alternative of Containment/Soil Washing continues to be the preferred option for this site. On the other hand, when implementing the "Worst Case" scenario into the evaluation it is possible to observe that the alternative Containment/Soil Washing/Bioremediation loses competitiveness in comparison with the Containment/Soil Washing option, due mostly to the nuisance to the surroundings caused by its prolongued operation time. The obtained results confirm the selection of the Containment/Soil Washing option as the most appropriate from all technologies to be applied at the study case contaminated site. Although this may be seen as a reflection of the low sensitivity of the system, it responds more to the elicitation of the goals itself, which have provided this – although more expensive- alternative with a high score in the hindering of nuisance to the surroundings as well as the fact that the technology can be easily implemented and it is largely demonstrated, apart for being an alternative that could occupy large local resources in its operation, entailing a strong social component.

4.5 Results of the Industrial Sites Land Register in the Region of the Bio Bio, Chile

4.5.1 Land register of suspicious sites in the Bio-Bio Region

After collecting the information concerning all activities or industrial branches that may be considered as potential sources of pollution of soil and groundwater, a thorough selection and classification was carried out, aiming to identify the provinces of the Region that would be considered as priority to conduct the risk assessment process [180],[232]. For this matter, the identified sites potentially contaminated (SPC) were distributed among the four provinces of the Bio Bio Region. The results of this classification are shown in Figure 74 and Table 59. An important aspect to consider is that the SPC list has been performed in order to demonstrate the number of sites in the VIII Region of Bio-Bio, without taking into account the size, potential impact, or current status. Quite a large number of these sites could be completely discarded after the completion of the first risk assessment procedure.

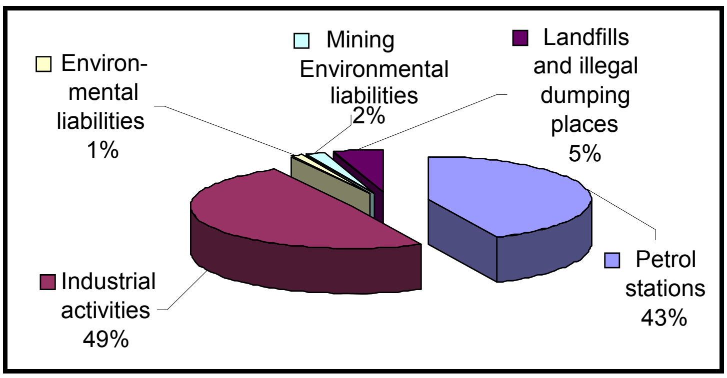


Figure 74. Percentage distribution of the identified sites potentially contaminated (SPC) in the Bio Bio Region for the five categories defined by CONAMA.

Table 59. Distribution of the identified SPC across the four provinces of the Bio Bio Region.

Province	Number of sites according to the classification of CONAMA					Total SPC in province
	Industrial	Environmental Liabilities	Mining Env. Liabilities	Dumping Sites	Petrol Stations	
Arauco	33	3	0	3	19	58
Bio Bio	92	0	0	7	46	145
Concepción	71	1	7	4	85	168
Ñuble	53	2	2	13	66	136
Total Region	**249**	**6**	**9**	**27**	**216**	**507**

The results of this inventory show that in the Region of the Bio Bio there are 507 Sites Potentially Contaminated (SPC), from which 249 emerge from industrial activities (see Table 60 and Figure 75 for a more detailed distribution by industrial branches).

Table 60. Distribution of SPC among the industrial activities operating in the Bio Bio Region

Industrial Activity	Number of suspected contaminated sites
Basic steel industry	1
Milk and milk products industry	18
Packaging of marine products	4
Fish flour production	12
Sugar production	2
Dye and finished textiles manufacture	4
Sawmills	170
Fiber panels production	12
Pulp, paper and cardboard manufacture	5
Chemical agents manufacture	8
Petroleum refineries	1
Cement production	3
Glass manufacture	1
Manufacture of metallic products	5
Marine shipyards and arsenals	3

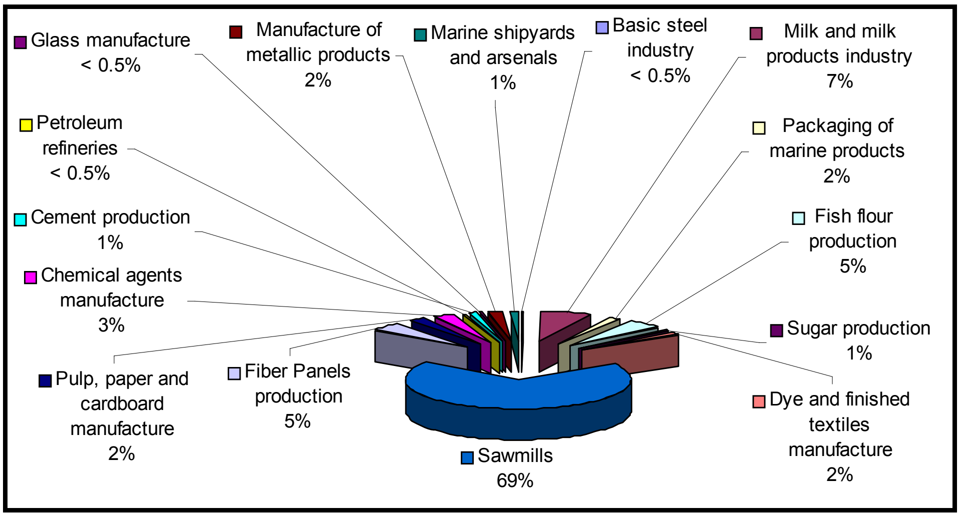


Figure 75. Distribution of SPC among different industrial branches of the Bio Bio Region.

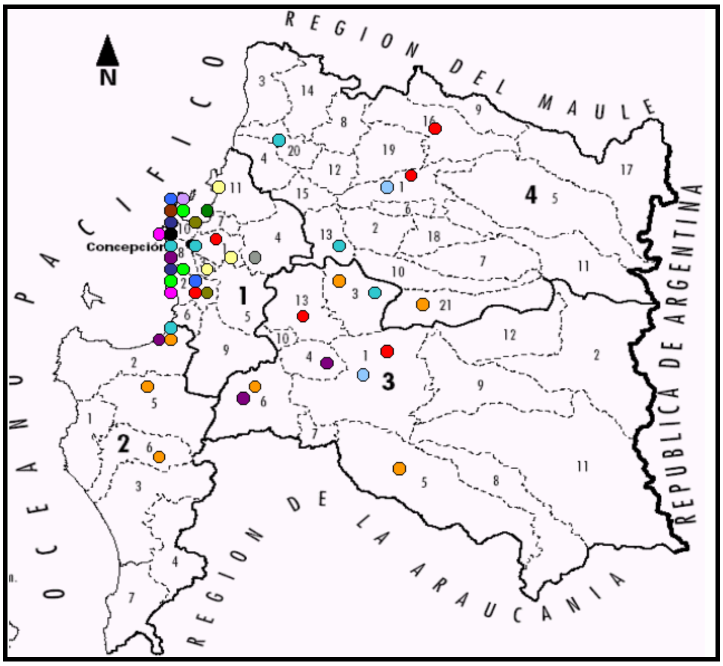


Figure 76. Geographical distribution of the occurrence of suspected contaminated sites (SPC) according to the type of activities in the VIII Region of Chile [180].

The high percentage of SPC from industrial activities shows the strong influence of the Region's industrialization process, which creates or at least pose a risk of damages to soils and groundwater in the Region. It may be observed that the forest activity in the Region explains the high number of sawmills and wood-related enterprises, in whose properties the presence of SPC can be considered as highly probable due to the use of pentachlorophenol (PCP), especially in those companies that operated before 1998, the year when the use of this reagent for wood conservation processes was forbidden by the Chilean government. From Table 59 it can be seen that each province has a number of SPC that depends on the activities that take place or that historically have taken place over there. The quantity of SPC varies from one province to another, according to each degree of industrial development.

After a thorough process of identifying the most vulnerable areas for human population, biota, groundwaters, and soil use in the Region, it was possible to determine the most interesting areas for conducting further investigations [232]. The results of the identification of the areas of interest can be observed in Annex VI. In accordance with the dispositions of CONAMA, the provinces of Concepción and Arauco have been considered as priority provinces, as they comprise the most industrially developed zones in the Region. Nonetheless, it is intended to apply the same investigation and evaluation process for the SPC found in the two remaining provinces, i.e. Bio Bio and Nuble, also. For the two priority provinces, an identification process of the areas of interest (communes) has been carried out, to limit the investigations to these zones only. For this purpose, the spatial distribution of the SPC in the Region has been compiled (Figure 76). On basis of this distribution, six communities of the province of Concepción, and four communities of the province of Arauco have been identified as areas of interest. The distribution of SPC in the selected communities of the priority provinces is given in Table 61 and Table 62.

Table 61. Distribution of the identified SPC in communities of the Concepción province.

Commune	Number of sites according to the classification of CONAMA					Total SPC in community
	Industrial	Environmental Liabilities	Mining Env. Liabilities	Dumping Sites	Petrol Stations	
Lota	2	0	2	0	4	8
Coronel	8	0	5	1	7	21
Talcahuano	30	0	0	1	17	48
Hualpén	4	0	0	0	4	8
Penco	4	0	0	1	7	12
Concepción	3	0	0	0	33	36
Total Province	**51**	**0**	**7**	**3**	**72**	**133**

Table 62. Distribution of the identified SPC among the communes of the Arauco province

Commune	Number of sites according to the classification of CONAMA					Total SPC in community
	Industrial	Environmental Liabiltites	Mining Env. Liabilities	Dumping Sites	Petrol Stations	
Arauco	9	0	0	0	4	13
Curanilahue	7	0	0	0	3	10
Los Alamos	9	2	0	1	2	14
Cañete	5	1	0	1	4	11
Total Province	**30**	**3**	**0**	**2**	**13**	**48**

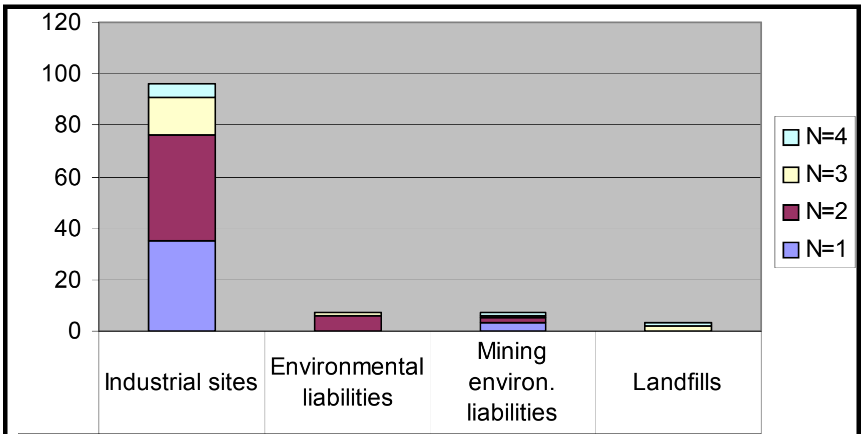
The selected communities of the priority provinces comprise a large number of the identified SPC in the Region of the Bio Bio. In special, the province of Concepción is one of the most industrialized provinces in Chile, whereas in the province of Arauco a great number of wood industry and sawmills is settled, where until recently PCP was used in the production processes. The selection of these two provinces and their communities most influenced by the presence of SPC will contain the most notorious and impacting sites of the Region.

4.5.2 Endangered environmental goods

In the context of the evaluation of environmental endangerment from surfaces under suspicion (first risk assessment) it is possibly to determine the environmental goods that are affected. Table 63 and Figure 77 show the frequency of the environmental goods endangerment in the evaluated surfaces under suspicion. Figure 78 and Figure 79 present the percentages of the frequency of endangerment for each environmental good [233].

Table 63. Frequency of endangerment for individual environmental goods at the evaluated sites suspected of contamination [233].

Site classification	Number of sites with endangerment to environmental good				
	Groundwater	Surface Water	Air	Soil	Other
Industrial sites	56	13	17	95	0
Environmental liabilities	4	2	1	7	0
Mining environmental liabilities	3	0	3	3	1
Landfills	6	2	0	7	0
TOTAL	**69**	**17**	**21**	**112**	**1**



	Industrial sites	Environmental liabilities	Mining environ. liabilities	Landfills
N=4	5	0	1	1
N=3	15	1	1	2
N=2	41	6	2	0
N=1	35	0	3	0

Figure 77. Number of endangered environmental goods by type of investigated site

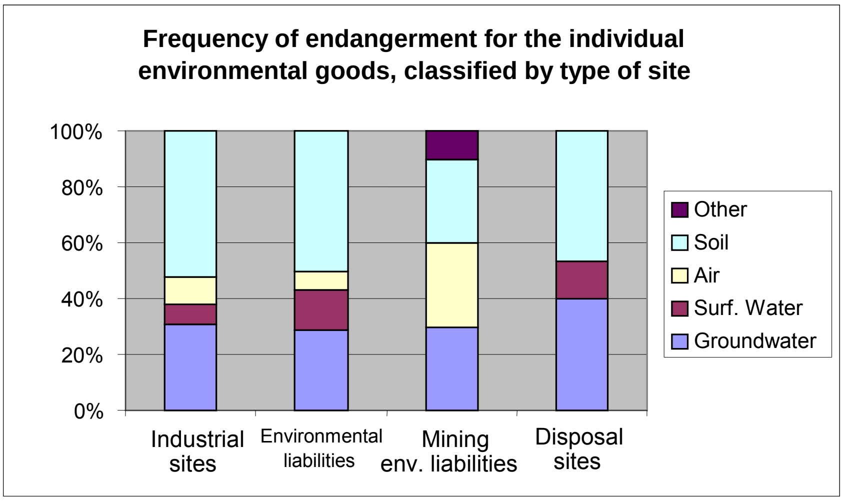


Figure 78. Frequency of endangerment for the individual environmental goods at the evaluated sites suspected of contamination (in percentage for the individual site classes).

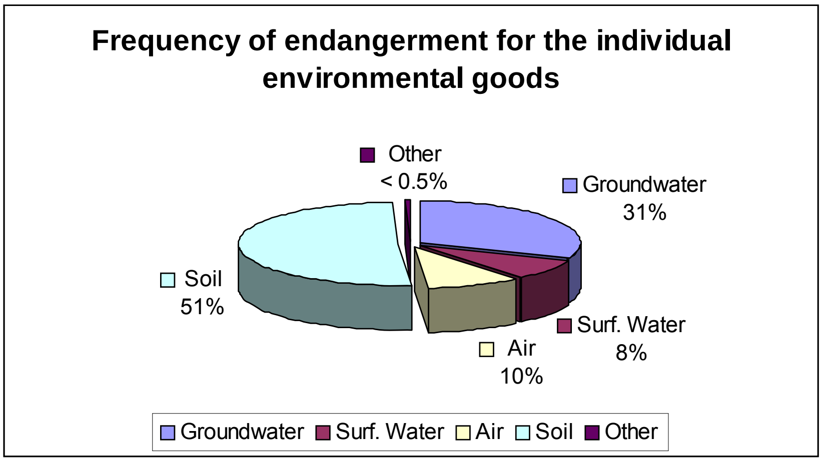


Figure 79. Frequency of endangerment for the individual environmental goods at the evaluated sites suspected of contamination (in percentage of total numbers).

4.5.3 Results from the first risk assessment

The risk assessment has been performed for all 181 identified sites. The following Figures (Figure 80 to Figure 83) represent the results of the first risk assessment evaluation for industrial sites, landfills as well as for mining environmental liabilities and environmental liabilities.

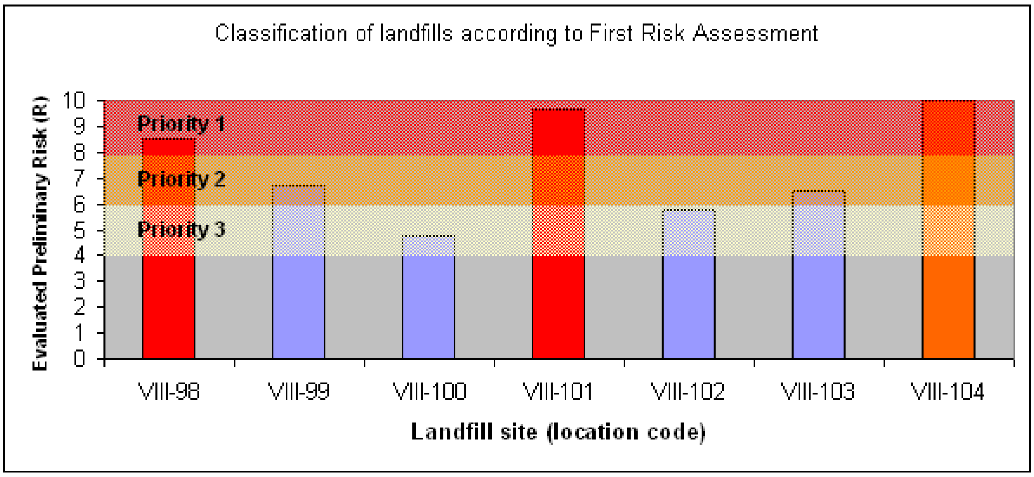


Figure 80. Summary of the resulting first risk assessment for landfill sites

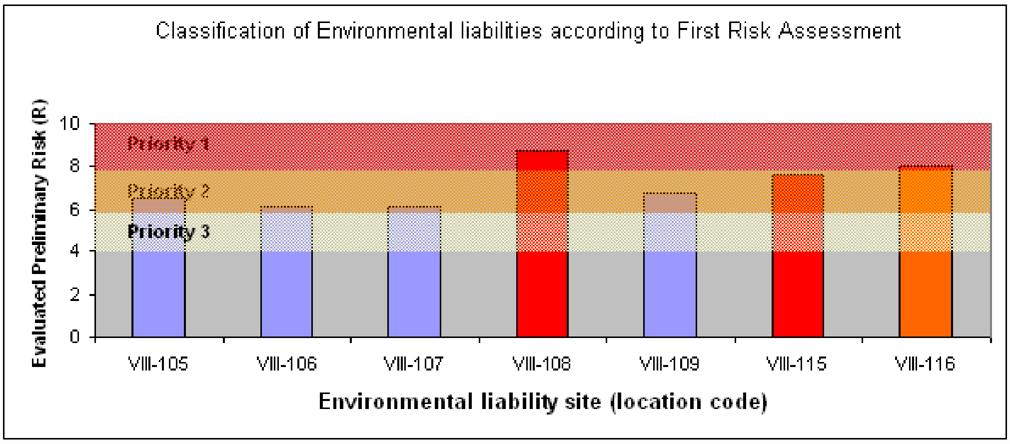


Figure 81. Summary of the resulting first risk assessment for environmental liabilities.

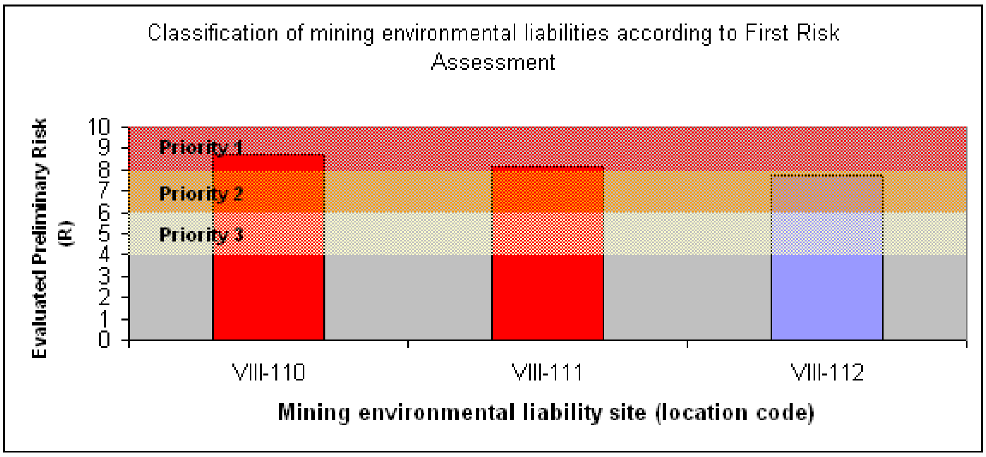


Figure 82. Summary of the resulting first risk assessment for mining environmental liabilites.

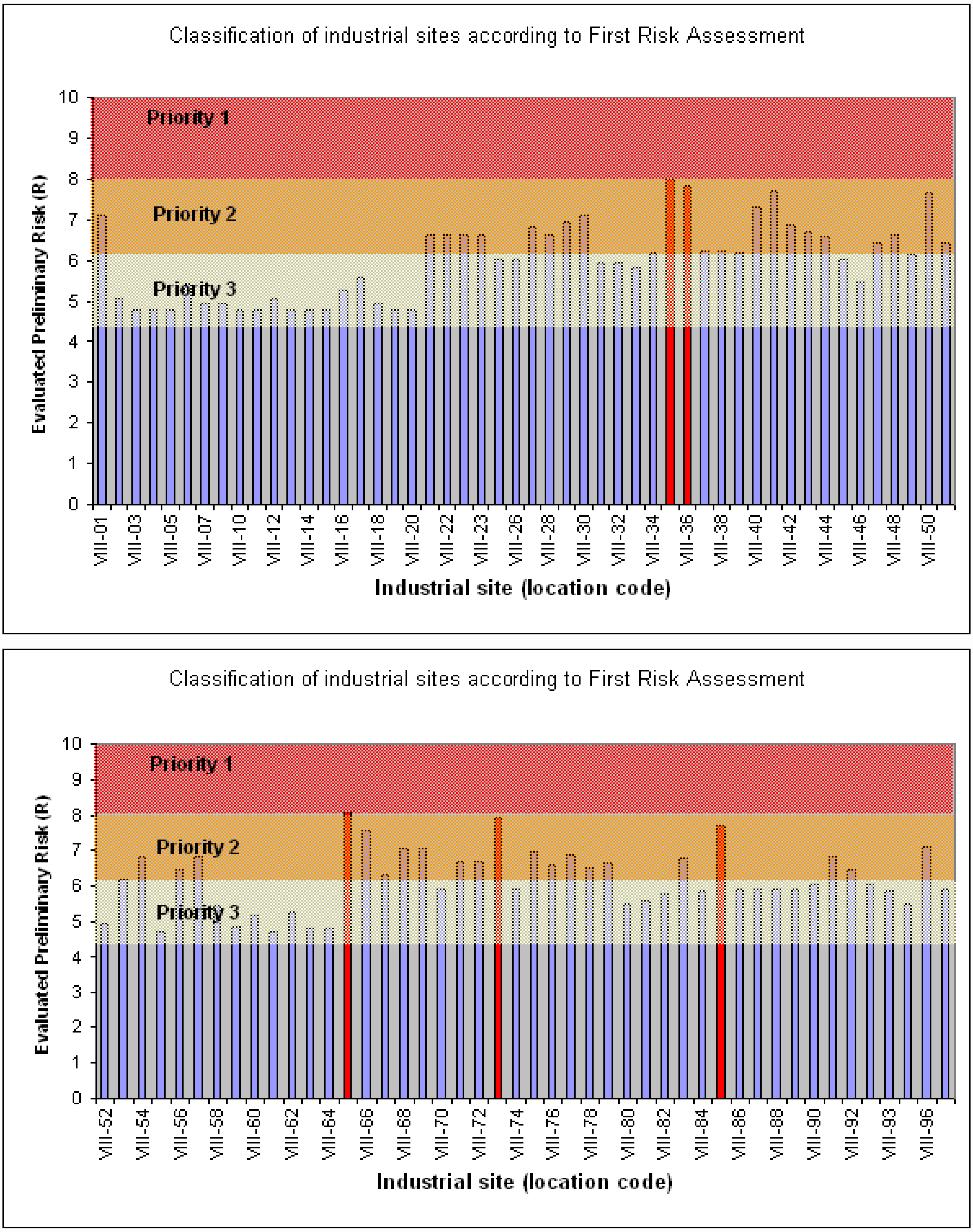
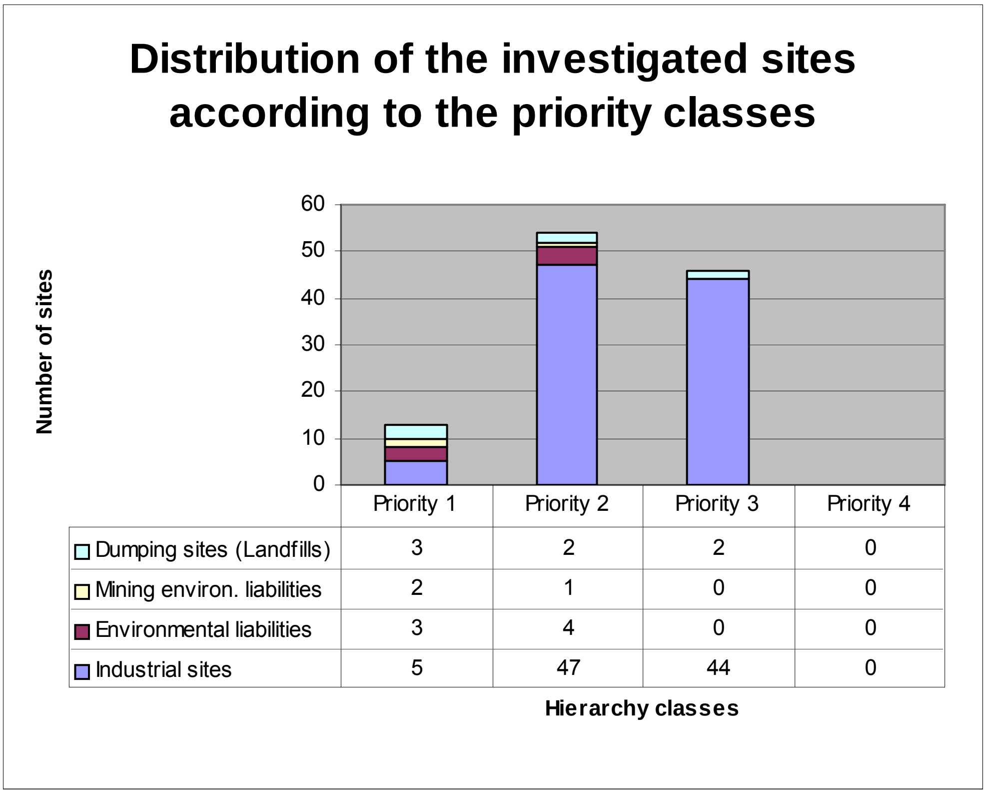


Figure 83. Summary of the resulting first risk assessment for industrial sites.

Figure 84 summarizes the results from the first risk assessment procedure. In the addressed provinces the amount of sites classified as Priority 1 adds up to 11% of the identified SPC. In addition, the sites classified under Priority 2 and Priority 3 comprise 48% and 41% of the identified SPC, respectively.

It must be once again stated that all sites classified under Priority 3 are subjects for further evaluations to determine their actual risk to human health and the environment. No single site has been classified as Priority 4 (i.e. harmless and not considered in further risk evaluation procedures).



	Priority 1	Priority 2	Priority 3	Priority 4
Dumping sites (Landfills)	3	2	2	0
Mining environ. liabilities	2	1	0	0
Environmental liabilities	3	4	0	0
Industrial sites	5	47	44	0

Figure 84. Hierarchy of SPC in the addressed communities of the provinces of Concepción and Arauco, resulting from the first risk assessment evaluation.

The performed risk assessment analysis could discern the sites that will require further investigations and the urgency of such. This classification permits to obtain a first overview of the contaminated sites situation in the Region of the Bio Bio.

Because of the highly developed industrial sector of the evaluated communities in the Concepción and Arauco provinces, a large number of sites that have been under suspicion of contamination were finally classified as actual hazards to the surrounding environment. As a matter of fact, no site was discarded as harmless in this first stage of evaluation.

It has been found that 13 sites can be classified under Priority 1, and 54 under Priority 2. The sites identified by the methodology described will have to undergo a further investigation and evaluation procedure to decide about their actual risk as well as the most appropriate remedial option to prevent further impacts on their surroundings.

4.5.4 Results of the second risk assessment

The application of the second risk assessment methodology for the 25 sites identified in the previous stage was based mainly on the SPC inspection form, which was filled in the site visits made by the work team and complemented with the historical information compiled by the analysts. Resulting from this analysis is the value of 'R' (i.e., total risk value associated to the site), which permits the classification of the sites within a priority rank, and suggesting the possible future actions to be taken by the corresponding organisms and authorities. The results of the second risk analysis are shown in Figure 85.

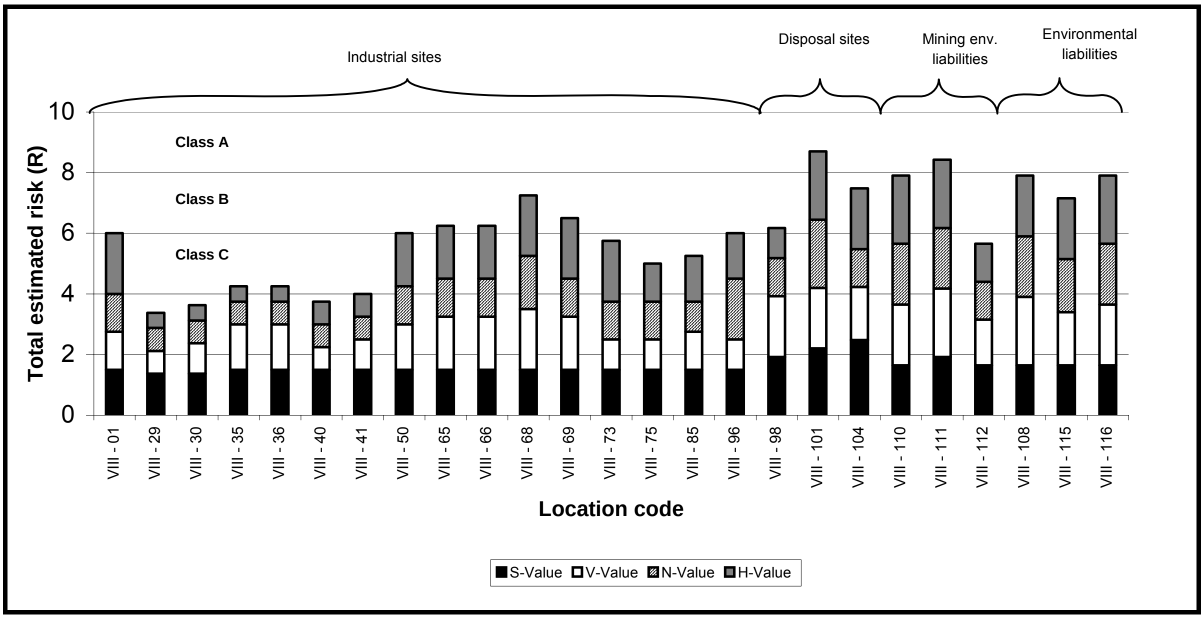
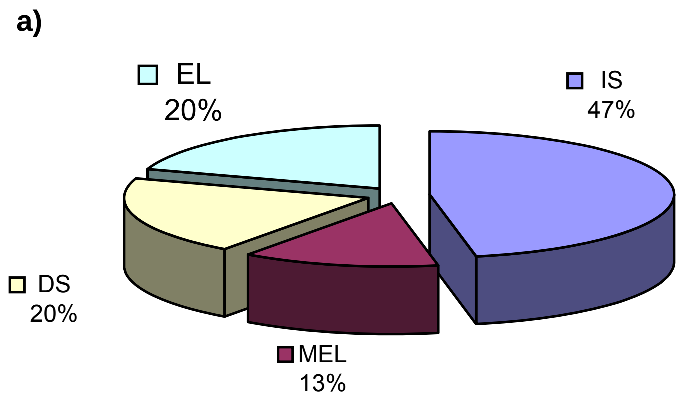


Figure 85. Results of the second risk evaluation for the 25 sites identified in the first risk analysis.

From the obtained results it is observed that 15 sites (i.e., 40% of the assessed sites in this stage) are classified either under Class A or Class B. This high percentage was expected since the assessed sites corresponded to the highest ranks from the first risk evaluation. Figure 86a presents the distribution of these sites according to their type of activity. Another important point to analyse is the distribution of these sites among the investigated communities. In Figure 86b it is appraised that the 15 sites Class A and Class B are homogeneously distributed in the provinces of Concepción and Arauco.

It is important to emphasize that although the goal of this work was to provide with the list of the Class A sites in the provinces of Concepción and Arauco for future detailed investigations, according to the obtained results the investigation of the 10 remaining sites classified as Class B is necessary as well. These sites can be source of risk for the health of the population and/or the environment. For that reason their further monitoring, control and future detailed investigations is recommended.



Legend:
EL: Environmental liability, DS: Disposal site, MEL: Mining environmental liability, IS: Industrial site.

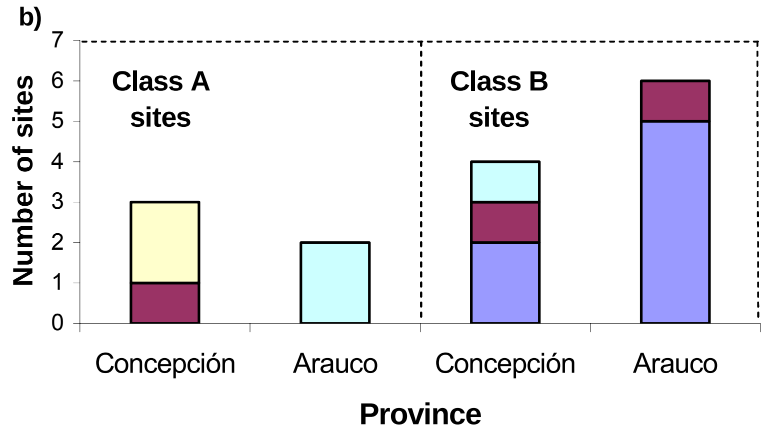


Figure 86. Distribution of the Class A and Class B sites according to: (a) their industrial activity, and (b) their location in the assessed provinces of the Region of the Bio Bio.

4.6 Application and adaptation of the developed knowledge-based tool for contaminated sites management in Chile

The knowledge-based tool developed in this thesis has been built based on existing European (Austrian and German) and U.S. American know-how and experiences of methods and technologies applied in these countries for contaminated sites management, as presented in Chapter 2. The system also considers an analysis and involvement of the social, economic, environmental, organizational and institutional aspects of thei conducted remedial projects, methods, and technologies.

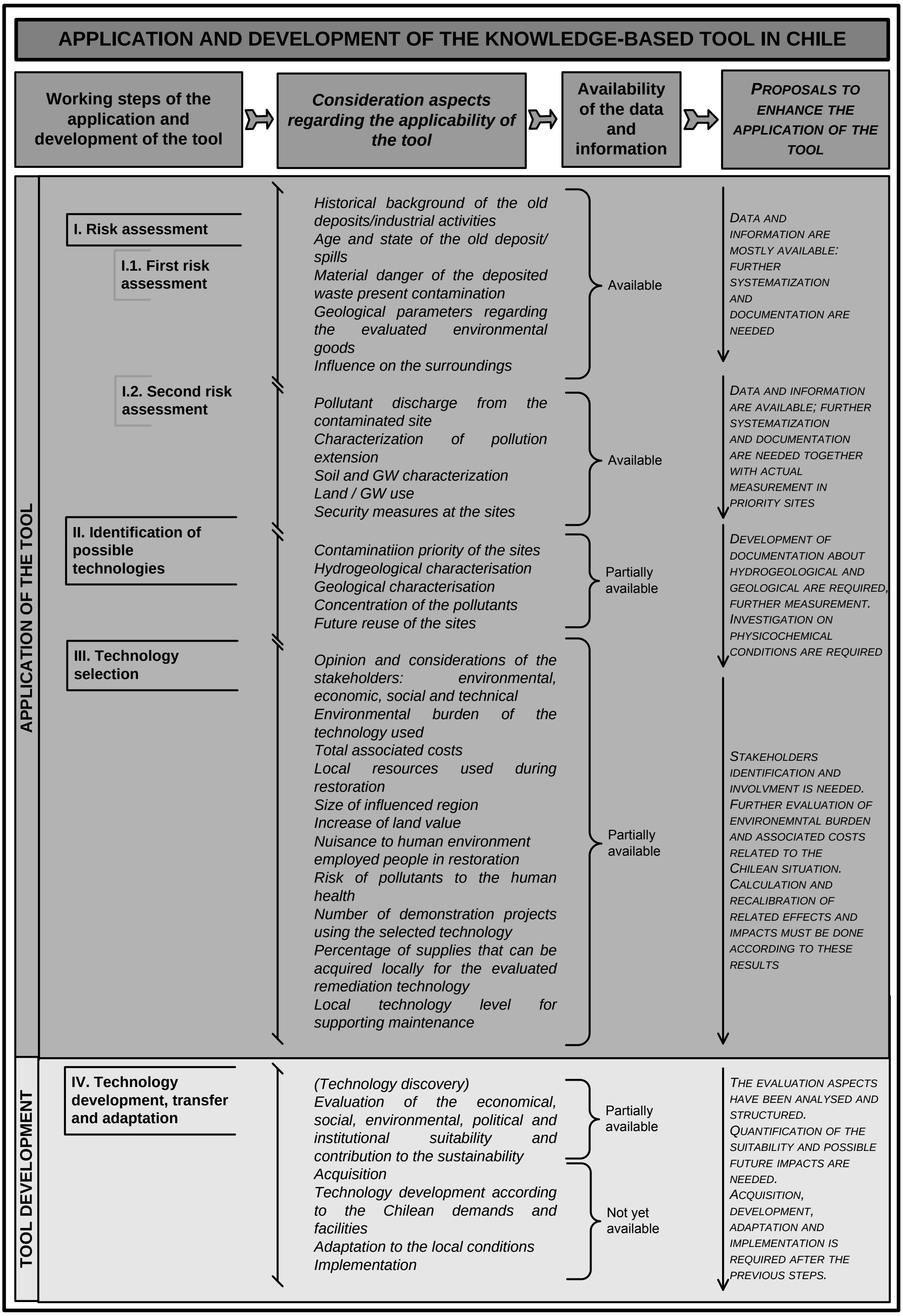


Figure 87. Achieved and planned work steps for applying, developing, transferring and adopting the knowledge-based tool for the remediation of Chilean contaminated sites

To validate this tool, its application in an Austrian study case (as described in Chapter 4) was performed. The results of such validation process confirm the soundness of the built structure and methods, such as the completeness of the evaluated factors. The pertinence of the tool has been then proved when compared to the conducted experiences in developed and industrialized countries.

It can therefore be stated that the application of this tool in Chile is reasonable. However, since the tool was developed in accordance to the conditions of industrialized countries, many aspects have to be estimated, evaluated, analysed and reformulated to achieve a suitable adaptation for the Chilean situation. These aspects consist of political and administrative background, the regulations on contaminated sites at national and regional levels, as well as the consideration of the adaptability of the tool.

The first part of this chapter horizontally summarizes, assesses and evaluates the applicability of the knowledge-based tool by following the main steps of the process, namely its risk assessment procedures, as welll as the identification and selection modules for establishing the most suitable technologies. Furthermore, a vertical dimension of the analysis determines a list of the available information for utilizing the tool in Chile, to finally make proposals for the necessary investigations to collect the required data and to enhance the developed knowledge-based model by adapting it to the local conditions. The chapter also contains the descriptions of the conditions and provisions needed for a future technology transfer, improvement and appropriate adaptation based on the Chilean technological and economic situation, social, infrastructural and environmental conditions, in line with the national policy and future objectives.

The summary of both application and development of the knowledge-based tool is represented in Figure 87, page 154.

4.6.1 Application of the risk assessment module

The carried out risk assessment procedures (as described in Chapter 3 and Chapter 4), are aiming to identify and classify sites suspected of contamination. To achieve that, the general conditions of the identified sites under suspicion of contamination are taken into consideration as well as the industrial activities that have been carried out on the site. To accomplish successfully the risk assessment, the following data and information are necessary:

- Historical background of the old deposits/industrial activities
- Age and state of the old deposit / spills
- Material danger of the deposited waste / present contamination
- Geological parameters regarding the evaluated environmental goods
- Influence on the surroundings
- Pollutant discharge from the contaminated site
- Characterization of pollution extension
- Soil and groundwater characterization

- Land and groundwater use
- Security measures at the sites

For the application of the tool in the European contaminated sites, all the information was available or has been processed during this work. The status of the existing data and information for the fulfilment of the risk assessment in Chile is described hereafter:

- During the implementation of the risk assessment procedure in Chile, within the framework of this Ph.D. work, the necessary data and information for the identification and primary evaluation of the sites under suspicion of contamination have recently been collected for the Region of the Bio Bio (i.e., historical description and register of industrial activities). Therefore the risk assessment procedure in its two steps could be successfully implemented and the first sites priority ranking could be performed.

- As further objectives, the analysis of the obtained information on the conditions at the sites and the subsequent recalibration of the parameters for both the first and second risk assessment processes are foreseen. This recalibration process should be supported by the chemical and hidro-geological characterization of each of the sites classified as Class A or Class B in the Region of the Bio Bio (see Chapter 4) by conducting a systematic soil and groundwater sampling and analysis. Such iterative calibration would bring a more suitable evaluation and risk assessment of the local conditions in this Region.

4.6.2 Application of the modules for identification of the most appropriate technology for contaminated sites management

The selection process for determination of the most suitable technological alternatives for the management of a contaminated site has been separated in two steps: identification of technically suitable technological alternatives, and the involvement of the identified stakeholders for determining the best solution through the analysis of their opinions and individual goals. For the identification of technically suitable technologies for the remediation of the contaminated sites, the needed information is mentioned as follows:

- Site priority according to their contamination and risk levels
- Hydrogeological and geological characterization
- Concentration of the pollutants
- Selected future redevelopment or soil use of the site

Moreover, for the selection of the best suitable technology, the following information is needed:

- Opinion of the stakeholders on technical, environmental, economic and social goals
- Environmental burdens of evaluated technologies
- Total associated costs
- Local resources used during restoration activities
- Extension of the influenced region by the contaminated site

- Change of land value
- Nuisance to human environment
- People employed in restoration
- Risk of pollutants to the human health
- Number of demonstration projects using the selected technology
- Percentage of supplies that can be locally acquired for the proper functioning of the selected technology
- Local technological level for supporting maintenance

Whilst all the necessary information could be gathered for the application of the tool in the Austrian study cases, in Chile, although some data (especially general hydrogeological aspects of the locations) is available, there is a lack of information regarding three important aspects. First, there is no information about the recurrence, quantity and impact of the characteristic pollutants in the Region of the Bio Bio. Secondly, it is important to consider that the contaminated sites-related policies and regulations are still under evaluation and development. This fact hinders the proper organization of all involved stakeholders for a common incorporation of their opinions and goals into the weighting system of the selection module. And finally, apart from excavation and disposal, no further technical alternatives are yet available in Chile for site containment and/or soil and groundwater remediation.

The following steps can be considered for solving the first two described aspects:

- From the carried out investigations and risk evaluations to the sites under suspicion of contamination in the Region of the Bio Bio, the most vulnerable areas as well as the most risk-posing sites have been determined (i.e., Class A and Class B sites). A further step of the work will contain the characterization of the identified priority sites in terms of their contamination and of their hydro-geological situation. These results will support the determination of the most suitable technical alternatives for the investigated locations, as well as their applicability to the largest number of sites

- The use of the developed procedure for the identification of suitable technologies can then bring an excellent tool to analyze the obtained information and to determine, under a European technical perspective, the most reasonable technologies that should be implemented for the Chilean situation.

- It is essential to determine the future institutions involved in a remedial project. During the carried out work it was possible to establish the first operative Committee on Contaminated Sites in the Region of the Bio Bio. This Committee could be considered as the corner stone for establishing an institution in the Region of the Bio Bio that should determine the multi-sectorial public objectives of the remedial actions to be taken in the identified contaminated sites. However, this suggestion should only be taken into consideration if the coming policy on contaminated sites does not explicitly determine an institution with this responsibility.

- The institution determined above should then be considered as one of the public stakeholders that should decide on the execution of management measures in contaminated sites remedial projects: However, various additional stakeholders should also be considered at certain levels of the decision making process to each specific project, such a private institutions as well as the community.

- Once all stakeholders are identified, the calibration process of the developed selection module can be performed for establishing an adequate goal system through consideration all the expressed opinions quantitatively.

- As fore mentioned, the implementation of the technology selection procedures is closely related to the type of technologies that shall be implemented in Chile for the management of contaminated sites. The calibration of the developed tool can only be performed once the conditions for remedial projects are known. For that reason, a technology transfer process is suggested, which should follow the guidelines underlined in the next chapters.

For the lack of technical alternatives in Chile it is stated that a technological transfer should be conducted in order to determine an appropriate implementation of the knowledge-based tool in Chile. The following sections introduce some guidelines for the establishment of a technological transfer from Austria (and Europe) to the Chilean situation in the field of contaminated sites management.

4.6.2.1 Technology transfer and adaptation

The origins of the word “technology” can be found in the Greek word technologia (τεχνολογια), which is a combination of techne (τεχνη) "craft" + logia (λογια) "saying". Thus, it is an encompassing term dealing with the use and knowledge of humanity's tools and crafts. Classically, it has been understood as a systematic implementation and application of human capabilities, arising from three interacting and coherent dynamic components of a human society: a technical-economical component with technical instruments, equipment and necessary infrastructure, a socio-political component with administrative and organizational structures, and a socio-cultural component, with standards, values and visions of the society using, demanding and developing technologies [234].

Nowadays, new definitions of “technology” have been developed to adapt it to the actual, changing world conditions. The New Technologies Research group of the International Institute of Applied System Analysis (IIASA) [235], defines technology as *the combination of* ***Hardware*** *(Manufactured objects),* ***Software*** *(Knowledge required to design, manufacture, and use technology hardware) and* ***Orgware*** *(Institutional settings and rules for the generation of technological knowledge and for the use of technologies)*.

From the two definitions presented above it is possible to state that technology is a complex issue that varies in time along with the society in a process known as *technological change*. Technology is therefore at the same time uncertain, dynamic, systemic and cumulative, as it continues its developing process within the context of a society. The crucial point whether technology can achieve something for humans, is therefore the effectiveness of the society's social organization. Thus, in the frame of the "appropriate technology concept", terms like self-development in the socio-cultural area, self-governing in the socio-political area and self-sufficiency in the technical-economical area, are important means for designing a technology adapted to the demand of the affected society. Hence, the appropriate technology concept means developing a flexible and participatory approach to economically viable, regionally applicable and sustainable technology [234],[236].

In this work, a detailed study has been carried out to determine the state-of-the-art methodologies and technologies for an integral site management. All these processes have been largely tested and proved over the last two decades in European as well as U.S. American site remediation and redevelopment projects. Nevertheless, the same addressed technologies are currently not applied in Chilean contaminated sites, as there is still a lack of standards and regulations as well as technical support for their appropriate implementation. Goal of this section is therefore to describe and asses the aspects, characteristics and conditions of a possible technology transfer of the pre-selected suitable technologies for the Chilean sites remediation.

By considering all of the above, this chapter introduces a brief introduction to technology transfer, and the further suggestions to establish the general steps for implementing the developed knowledge-based system to the Chilean situation.

4.6.2.2 The technology transfer process applied to the contaminated sites management situation in Chile

Technology transfer was written in legislation in the U.S.A. already in 1958 with the purpose of transferring technology between the federal laboratories and the private sector. There are many definitions for technology transfer, being a more general one the following: "a process in which technology originated in one place for one purpose is used elsewhere, for either the same or a different purpose" [237]. Such transfer can be performed either among **sectors** within one country (e.g., university, state, industry), or **geographical**: from one country to another one (which represents the case studied in this work).

The transfer of technologies is basic to the process of sustainable long-term socio-economic development. Any successful effort that addresses the technological transformation of enterprises based on technologies also needs to take into account economic and social considerations. Failing to take into account these two factors usually prevents the implementation of the addressed technology. In particular, failure to deal with employees (i.e., local work power) both in the design and implementation steps of the technology adaptation will prevent significant technology transformations to be carried out and will most likely imply negative effects on the local employment [238].

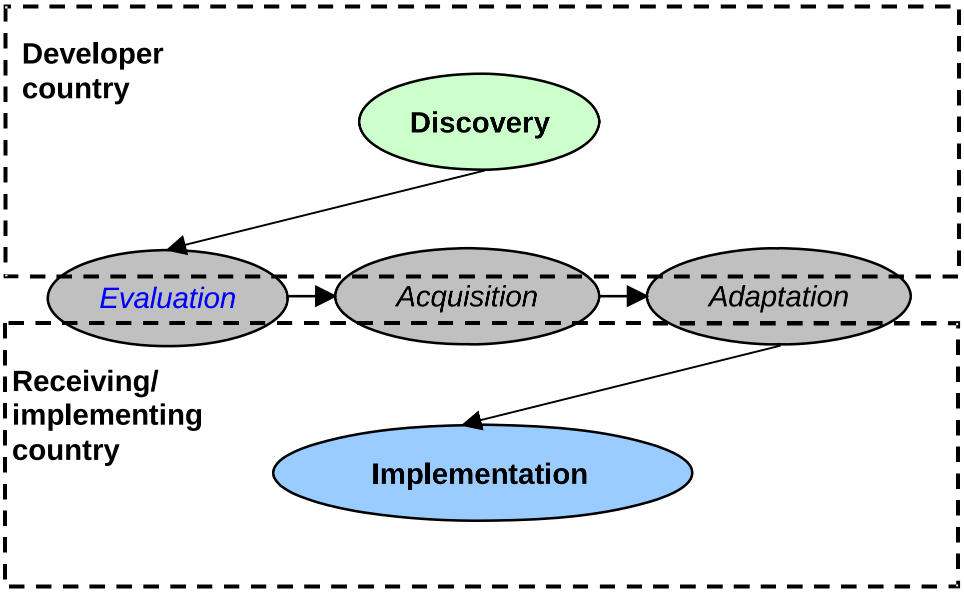


Figure 88. General steps for technology implementation

Geographical technology transfer typically involves the following steps: discovery, evaluation, acquisition, adaptation, and implementation, as observed in Figure 88. The first step of this process is achieved in the *developer* countries, and corresponds to the technology discovery. Once this technology has been established in the market, it must be evaluated by both parties, *developer* and *implementing* or *receiving country*, for its suitability (in the praxis technical and economical suitability in the beginning, being social and environmental parameters also considered in later discussions and evaluations) in the receiving region. After convincingly establishing its suitability, the technology is acquired and adapted to the local conditions of the receiving country for an future implementation. Figure 89 shows the described dimensions of the technology transfer process.

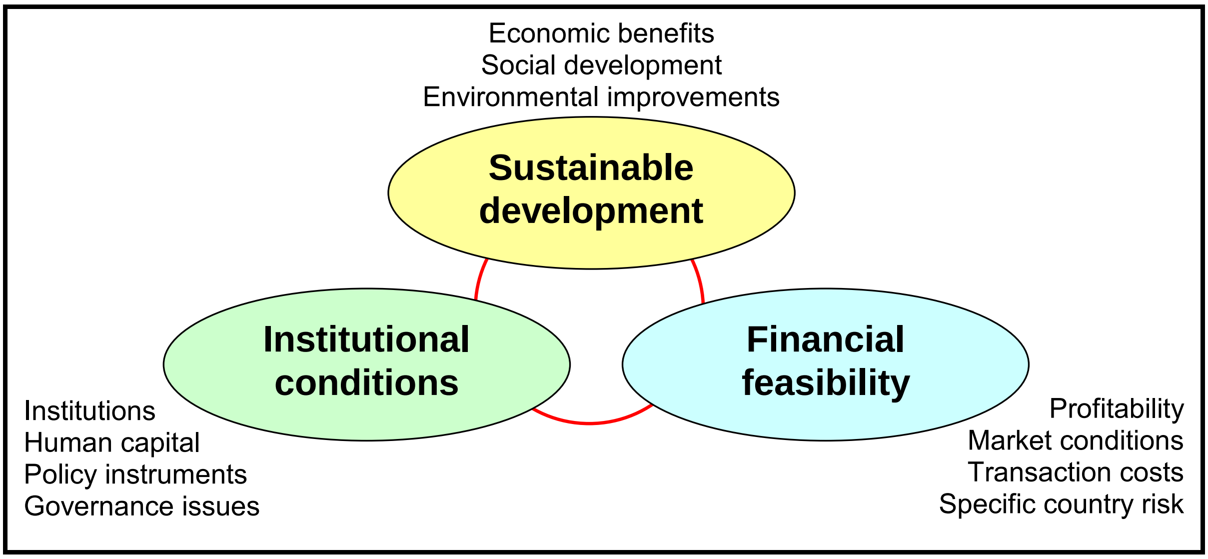


Figure 89. Dimensions and interactions of a technology transfer process (adapted from [239]).

Table 64. Possible favourable and constrictive conditions for technology development and transfer in developing countries (adapted from [240],[241]).

Institutional factors	Favourable conditions	Constrictive conditions
Government policies and support	- development of clear guidelines for managing contaminated sites - promote efficient institutional structures - promotion of local industries and private sector - fostering programmes for raising the community's awareness - introduction of fiscal incentives (subsidies and/or reductions in tax payments for environmental restoration projects) - fostering the interaction between industrial sectors and universities, in order to accomplish practical data to form the information basis for establishing a general management strategy of contaminated sites (e.g., from a costs point of view, it could be determined that the containment technologies should be first evaluated for implementation, while waiting for further budgets for remedial projects)	- inefficient administrations in terms of management or financial capacities - bureaucracy levels may determine the involvement of a large number of stakeholders - misuse of fiscal incentives (tax breakers)
Industry and technology	- involvement of private companies - incentives to transparency in accountability, in order to involve local micro- or small enterprises (MSEs) together with large (and many times international) service-providing companies - promotion of simple and labour-intensive methods in the adaptation of technologies - promotion of interactions between industry and university, in order to achieve large efforts in adapting technologies for the remediation or containment to the local conditions through an empirical, scientific and technical demonstration, and/or to develop new technological alternatives, more in accordance to the local technological and structural situation.	- inadequate site investigations and information assessment - inappropriate designs - inappropriate selection of technological alternatives - lack of operation and maintenance - lack of research and development
Financial support	- incentive low rate loans for capital investments in environmental restoration projects - financing equipment - financing studies on technology adaptations or development of new technological alternatives	- if incentives are not performance-based, poor operational performance of technologies in remedial projects are expected to arise

For the case of technology transfer in the contaminated sites field, the general steps remain as above described. For this evaluation, the investigation of the following elements must be carried out:

1. Costs and benefits of the technology (technology acquisition, installation costs, operational costs, mainteinance, profitability, value added, etc.)
2. Existance of institutions for managing the transfer and all the related activities
    a. Government policies and support
    b. Involvement and promotion of industries
    c. Financial support (see Table 64 for more details)
3. Existance of know-how (i.e., “human capital”) in the receiving region
4. Availability of university and research institutes (to determine the scientific and technical support through the life cycle of the technology)
5. Availability of raw materials in the receiving region
6. Determination of the priorities established by the local policy-making body.
7. Suitable market conditions
8. Estimation of the social development and environmental improvement as associated impacts to the implementation of the technology.

Moreover, the adapting process of remedial technologies in a developing country can have several institutional fostering and hindering conditions, which are summarized in Table 64.

4.7 Synopsis of Chapter 4

This chapter presents the results and discussions of the elaborated new model introduced and described in Chapter 3.

The first risk assessment procedure entails a first, approximate analysis of variables that are usually easily obtained through a historical background investigation of the site. The second risk management procedure determines the actual endangerment caused by the evaluated site, considering a more detailed description of the conditions in the site and the actual present pollutants. Through this risk evaluation process it is possible to prioritise the sites under suspicion of contamination and even suggest a primary approach for the management measures to be taken at the site for the impairment of its associated risk. Secondly, the procedure for the identification of feasible site management alternatives entails the collection of the knowledge gained through years of experience in Europe (summarized in Chapter 2), to determine the technical feasibilities of different technological approaches for site remediation in a certain site in consideration. Finally, the procedure for the selection of the most appropriate technology entails the construction of a Balanced Scorecard in which the technology is not only economically evaluated, but also considers social, technical and political arguments which are evaluated by all stakeholders involved in the remedial project.

The developed risk assessment procedure has been utilized as part of the process for the identification and evaluation of sites suspected of contamination. Through this methodology the most vulnerable areas in the Region of the Bio Bio were established and thus the areas of interest within the Region could be identified. Chapter 4 introduces the first results of the land register of an industrial Chilean Region considering the existence of contaminated sites and their degree of influence on the human health and on the environment. Finally, this chapter also introduces the structure for a technology transfer in the field of contaminated sites management from the European experience to the Chilean situation. This technology transfer shall consider an evaluation of several aspects (i.e., policy and legislation, transport costs, implementation and operational costs, availability of local resources, financing alternatives, availability of local trained manpower, local scientific and technical support, among others) in order to determine the actual feasibility of suggesting a technological alternative for the management of contaminated sites in Chile.

5 Summary

The **introduction** of the present work (chapter1) establishes the need of an integrated decision tool for helping stakeholders in contaminated sites management projects, as various aspects (e.g. technical, economic, legal and social points of view) must be taken into account to accomplish an integral solution for the specific problems of each individual site. It is suggested and shown that the dimension of the contaminated sites problem is a worldwide concern, as there exists no complete data for determining the actual risk posed to human health and the environment. Moreover, in the last few years, developing countries have also started with evaluations of the national and regional contamination levels, and to look for the most appropriate legal and technical solutions for these situations. However, there is a lack of resources and experience that hinders this process. Considering all of this, the objective of this work was to develop a simple but robust system based on the international experience on contaminated sites management, especially taking into account the examples of Austria, Germany and the U.S.A. A further objective of this work was to establish a know-how transfer from Europe to Chile to help in the development of the legal and technical framework that is currently being developed by the Chilean National Environmental Commission (CONAMA) for the identification, evaluation and management of contaminated sites.

An overview of the **legal context** that frames contaminated sites management projects is presented in the **theoretical background** (chapter 2). A more comprehensive analysis is made on the Austrian legislation, basis for the development of the model at hand. This section introduces the **contaminated sites situation in Europe**, as well as the most relevant soil-related issues, aiming to demonstrate the actual dimension of the problem. Although there still is lack of information regarding this point, this section summarizes the current knowledge about the number, size and characterization of contaminated sites in European countries (which in many cases corresponds to the estimation of the actual figures). The main problems commonly associated with contaminated sites are discussed as well. Their common pathways and their direct and indirect effects on the environment and human health are also introduced.

Risk assessment focused on the evaluation of contaminated sites is generally described. Two risk assessment evaluation methods are also presented, namely the EVAPASSOLD model and the Baden-Württemberg site evaluation procedure. Both models are introduced, as they are the basis of the risk assessment conducted through the developed model.

A thorough description of the **state of the art technologies and methodologies for contaminated sites managemen**t is also given in the theoretical background section (chapter 2). An outline of the latest discussions and information about investigation and evaluation of contaminated sites is presented too. The most commonly applied **containment technologies** are also identified and illustrated, as well as the **remedial options for soil and groundwater**. Guidelines for the selection and implementation of such technologies are provided by considering the hydrogeological conditions of the site and its occurring pollutants that characterize it. A comprehensive comparison between different technologies in terms of their application methods (i.e., in-situ, ex-situ, on-site and off-site) as well as their nature (active or passive hydraulic measures, and physical, biological or chemical treatments) is also given. The associated costs and technical restrictions for different technological alternatives are also provided in this comparison. The state of the art evaluation presented in chapter 2 contemplates the introduction of a recently included topic in contaminated sites management programs such as the **redevelopment of sites** after the remediation program. An overview of the redevelopment project structure is given, identifying both the stakeholders participating in such decisions, as well as the advantages that are coupled with the integration of this new aspect into site management projects.

Finally, this section (chapter 2) introduces the basics of **decision-making theory** in order to establish the main features to be developed for constructing a reliable tool to help decision-makers in environmental projects.

In the **methods and practical approach** section (chapter 3), the strategy followed for the construction of the knowledge-based tool for contaminated sites management is introduced. The selected strategy involves first the development of a **preliminary risk assessment evaluation**, based on the EVAPASSOLD model for small old deposits and the Baden-Württemberg site evaluation procedure. A **second risk assessment evaluation** follows the Baden-Württemberg procedure, together with simplifications provided by previous studies. The second part of the followed strategy consists on the development of a **selection procedure for the feasible technological alternatives for site management**. The fundamentals of this procedure are also presented in chapter 3. The third and last part of the proposed model deals with the **identification of the most appropriate technology for site management** through the application of a Balanced Scorecard, especially designed for this purpose. The steps followed for the formulation of this Balanced Scorecard are presented and described in extense. Finally, a risk assessment step is added for the suggested most appropriate technology to ensure its public acceptance. As for all developed models, a **validation procedure** is needed for both establishing its concordance with already executed projects and to calibrate the model in case of significant deviations when compared to case studies. In this work the model has been tested against an actual Austrian remedial project, which has been selected to determine the consistency of the model.

A major practical goal of this work is the knowledge transfer of the European experience to the Chilean reality. Prior to any discussion on the technical and legal aspects of the future remediation projects framework, the dimension of the contaminated sites problem must be quantified. Chapter 3 introduces the work undergone in cooperation with the Chilean National Environmental Commission (CONAMA VIII Region) for the **identification and preliminary risk assessment of potencially contaminated sites in the VIII Region of Chile.**

Chapter 4 presents the **results and discussions** of the elaborated new model. First, the developed risk assessment module is presented for the end user. The definition of the **first risk assessment procedure** contemplates a simple structure of elicitation for variables that are usually provided or that can be easily obtained through a historical background investigation of the site (i.e., material danger of the deposits or associated to the industrial activities, extension of the site, probability of contamination occurrence, and the complexity of the risk posed to the envisaged environmental goods). The first risk assessment procedure developed in this work provides a simple and robust approach for identifying the sites suspected of posing risks to the environment and to the human health. The **second risk management procedure** aims for the determination of the actual endangerment to these media, caused by the site specific risk. Since the second risk assessment procedure has already been tested in field projects along the past years, this evaluation method can be considered a reliable alternative for determining the cases in which a remedial project should be started.

The developed **selection procedure for feasible technological alternatives for site management** entails the collection of the knowledge gained through years of experience in Europe, especially in the German-speaking region (mainly considering Austria and Germany). Simple logical conditions and reasoning have been developed and applied to determine the technical feasibilities of different technological approaches for site remediation to the contaminated site in consideration. In order to organize the developed conditions, decision trees were established, in which the application of fuzzy logic was introduced to emulate the actual reasoning of human experts for establishing an answer to the problems. The developed module can therefore identify technically-feasible remedial options for the management of contaminated soil and groundwater.

The last developed module consists of a **procedure for the identification of the most appropriate technology for site management**. Following a logical framework approach, a Balanced Scorecard was constructed for the evaluation of the identified technically-suitable remedial options for the site into consideration. The Balanced Scorecard involves the end user (in this case the stakeholders of the remedial project) in providing their preferences of four different goals to be achieved (maximization of technological suitability, optimization of the regional social conditions, maximization of the economic competitiveness of the region and the minimization of the burden to environment and human health). After considering the stakeholders opinion, the system performs a comparison among all addressed technologies in order to determine and select the most appropriate one for the case in study.

Chapter 4 finally introduces the results of the **identification and preliminary risk assessment of potentially contaminated sites in the VIII Region of Chile**. The **areas of interest** were chosen through the identification of the most vulnerable areas in the region. Such an identification was necessary for the optimal utilization of resources available for the investigation by focusing on the most impacted zones. The historically-described sensible areas and sites on suspicion of contamination were identified. The performed risk assessment analysis also could discern the sites that will require further investigations and the urgency of such. This classification permits to obtain an overview of the actual contaminated sites situation in the Region of the Bio Bio.

6 Conclusions

Contaminated sites pose direct and indirect threats to environment and to human health. Decontamination or containment of pollutants from risk-posing areas should be therefore seen as an important aspect of national and regional environmental management policies.

Management of contaminated areas however should not be seen as an "one-size-fits-all" but rather a "tailor-made-solution" approach, due to the complexity of case-specific aspects that must be considered for determining the best solution for each individual site. Among these one can enumerate the legal framework, economic aspects, as well as social and environmentally-related considerations.

Considering all of the above and due to the large number of alternative technologies currently available for the management of contaminated sites, it is clear, that a decision support tool is needed. But so far, none of the available decision support tools has pursued to integrate the complete project management steps into one single, consistent approach.

Goal of this work was to develop an integrated tool for supporting contaminated sites management decisions, which also can be used as a know-how transfer tool for countries that are starting to deal with the contaminated sites problem.

6.1 Development of a knowledge-based system for supporting contaminated sites management projects

The knowledge-based system was structured in three separate modules: risk assessment, identification of technologically suitable remedial options, and selection of the most appropriate remedial solution. A database was developed with a comprehensive description of groundwater and soil containment as well as in-situ and ex-situ remediation technologies. The database includes information regarding the advantages and disadvantages of the selected technologies according to the site conditions and present pollutants, as well as the costs and environmental burdens associated to each one of them.

Based on previous risk assessment models, the first module stands as a simple method for identifying the most problematic sites, at which more detailed investigations should be carried out. The risk assessment model formulated in this work can be used with information collected in first site inspections and investigations and by bringing the historical background information of the site into play.

The second module for the selection of technically suitable options for the management of contaminated sites has introduced an interesting approach through the use of fuzzy logic for the formulation of the decision process. The use of this mathematical tool entails the advantage of working with a more flexible and natural environment, which suits to a decision process such as one regarding contaminated sites.

Finally, the construction of the third module has followed a multi-attribute conception of the contaminated sites problem to identify the most critical aspects considered by the project's stakeholders in their decisions. The developed Balanced Scorecard stands as a novel tool for the elicitation and selection of remedial options for contaminated sites. Through the accomplishment of a sensitivity analysis it has been demonstrated that the system is stable and robust in terms of the chosen elicitation schemes, and that the preferences of the different stakeholders are influencing factors on the final result.

The performed evaluation allows identifying and suggesting a remedial option that gives the best possible fit to the expectations of all stakeholders involved in the project. It also permits to rationalize the use of available resources in the most cost-consuming steps (i.e., identification and evaluation of sites suspected of contamination), and it provides with a consistent logical procedure for the determination of remedial options for each individual site. Such identified solution is given to all stakeholders as a suggestion for the procedure to be followed.

Although the final decision in practice will always be taken upon the common decision of the individual stakeholders, the developed system stands as a robust and consistent support for the decision-makers in contaminated sites management projects.

6.2 Know-how transfer program for helping in the first land register of the industrial VIII Region of Chile

An immediate use of the methodologies elaborated in this research was achieved through the collaborative work with the Chilean National Environmental Commission (CONAMA) and the University of Concepción, Chile.

In a first step of this study, a list of industrial activities of the Region of the Bio Bio was prepared. With the help of the Operative Committee on Contaminated Sites for the VIII Region of Chile, the historically-described sensible areas and sites under suspicion of contamination could be identified. Following the guidelines of the Chilean National Environmental Commission, the areas of interest were chosen in order to save the available resources for investigating the most impacted zones.

From this evaluation it could be determined that broad areas of the central valley and shoreline of the Bio Bio Region present a medium total vulnerability, a situation that must be considered in future risk analysis for the evaluation and determination of sites to be investigated. The same is valid for the areas that present a low vulnerability. In this case the regular monitoring by both the authorities and the community must be fostered in order to maintain this vulnerability value, therefore protecting the interests of both the community and the industrial sector carrying out its activities in those zones.

In the first risk assessment procedure, a total of 13 sites were classified under Priority 1, and 54 more under Priority 2. From these, a total of 25 sites have been considered to undergo a further investigation and evaluation procedure to decide about their actual risk and the most suitable remedial option to prevent further impacts on their surroundings. This second risk evaluation has concluded that 15 of the 25 assessed sites are classified either under Class A or Class B, and therefore entailing considerable risk potentials to the human health and environment that should be the driver for further studies to determine the containment or remediation alternatives to hinder a further propagation of their pollution to their surroundings.

The carried out methodology proved to enable the identification of sites that pose most danger to the surrounding human settlements and to the environment by using selected parameters. Furthermore, the evaluation of the probability of contamination and the classification of the selected sites has been carried out to define their actual risks. Thus, the use of this methodology, which can be part of a more complex site management toolset, allows authorities in developing countries to concentrate their efforts in solving the problems associated to the sites with a highest probable benefit for the population and for the surrounding environment, optimizing time and economic resources available.

6.3 Outlook

As for many new developed systems, several opportunities for improvement and further development can be spotted. For example, programming of the complete system under a single environment could result in a more user-friendly software tool.

In order to add a new dimension to the practical experience regarding the application of technologies suitable for the pollutants and the soil media in which they are present, a statistically-designed study for all addressed technologies and pollutants is suggested (in the form of a “design of experiments” procedure). The results of such a study could help to complement the empirical knowledge with statistically validated data that will definitely serve for the definition of the best solution in a technology selection procedure.

Concerning the further use of the developed system in Chile, it is planned to use the system to determine the adequate technological approaches for the management of these identified sites, whilst estimating the necessary materials and costs associated to their remedial operations. Such use is foreseen to start with the second semester of 2006.

By carrying out the steps described above, it is expected to gain a clearer picture of the contaminated sites existing in the VIII Region of Chile. Such knowledge will provide CONAMA with the necessary basis for a forthcoming discussion on how to establish the national legal framework regarding contaminated sites management in Chile.

7 Index

7.1 References

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7.2 Symbols and Abbreviations

%	Percentage
a	Year
A_i	Alternative in BSC model
ACA	Active Carbon Adsorption
AHP	Analytic Hierarchy Approach
ALSAG	Austrian Law for the clean-up of contaminated sites (Altlastensanierungsgesetz)
AOX	Halogenated Organic Compounds ('Adsorbable Organically bound halogens')
a_0	Duration of „opened“ deposit [a]
a_R	Duration of „closed“, recultivated deposit [a]
AS	Air stripping
AWG	Austrian Waste management act (Abfallwirtschaftsgesetz)
B-/AS	Bio-/Air Sparging

BAU	Construction waste landfill
BHR	Biological hydraulical remediation
BN	Proof level of the Baden-Württemberg model
BOD	Excavated soil landfill
BOD_5	Biological oxygen demand
BP	Results of the benchmarking process of technologies for soil and groundwater remediation
BSC	Balanced Scorecard
BTEX	Benzene, toluene, ethylbenzene, and xylene
B-Value	Pollution load characterization
BVE	In-situ bioventing, bioremediation technology
B-W	Baden-Württemberg
°C	Degree Celsius
C_i	Set of attributes in BSC model
C_3-C_{10}	Gasoline-range hydrocarbons
ca.	Circa. About
CAP	Capping technology
CEC	Cation exchange capacity
CEE	Central and eastern Europe
C_F	Concentration at the solid phase
CHC	Chlorinated hydrocarbons
CHO	Chemical oxidation
Cl	Chloride
ClO_2	Chlorine dioxide
cm	Centimeter
CO	Costs
COD	Chemical oxygen demand
CONAF	Corporación Nacional Forestal, Chile. National Forest Corporation
CONAMA	Chilean National Environmental Commission
COM	On-site composting¸ bioremediation technology
Corg	Organic carbon content
Cr	Chromium
Cu	Currency unit
C_w	Concentration in the water

DA	Decision analysis
DC	Decision context
DM	Decision-maker
dml	Dimensionless unit
DNAPL	Dense Non-Aqueous Phase Liquid
d.s.	Dry substance
DVO	Austrian Landfill ordinance (Deponieverordnung)
E_{0-1}	Historical evaluation according to the Baden-Württemberg model
E_{1-2}	Indicative/orientative investigations according to the Baden-Württemberg model
E_{2-3}	Detailed/Complete investigations according to the Baden-Württemberg model
E_{3-4}	Investigations for the proposal of containment and/or remediation measures alternatives according to the Baden-Württemberg model
EEA	European Environment Agency
e.g.	Exempli gratia. For example
ELE	Electrokinetic stabilization, in-situ technology
EPA	U.S. Environmental Protection Agency
etc	Et cetera. And the rest, and so forth
EU	European Union
EUR	Euro
EUS	End User
EVAPASSOLD	Evaluation and preliminary assessment of small old deposits
F	Determined data according to Baden-Württemberg model
f( )	Factor considering all geological parameters regarding the evaluated environmental goods according to the EVAPASSOLD model
f(A)	Risk of contamination effects on air according to the EVAPASSOLD model
f(Env.Goods)	Function of the relevance of the environmental goods for the propagation of the contamination.
f(Extension)	Indicator of the site's extension in terms of quantified characteristics
f(G)	Risk of contamination effects on groundwater according to the EVAPASSOLD model
f(P)	Probability of occurrence for the endangerment of environmental goods
f(S)	Risk of contamination effects on soil according to the EVAPASSOLD model
f(W)	Risk of contamination effects on surface water according to the EVAPASSOLD model
Fe	Iron

Fe^0	Zero-valent iron
FE	Feasibility
FEA	Federal Environmental Agency (Austria)
GAS	Air sparging bioremediation, Passive measure technology
H_2O_2	Hydrogen peroxide
H-Value	Toxicological risk evaluation
ha	Hectare, 10000 m²
HC	Hydrocarbons
HDPE	High Density Polyethylene
HTTD	High temperature thermal desorption
i.e.	Id est. That is
IE	Ion exchange
INC	Off-site incineration, thermal treatment technology
INFOR	National Forest Institute, Chile
I_0	Infiltration into „opened“ landfill [mm/a]
I_R	Infiltration into „closed“, recultivated landfill [mm/a]
I.V.	Inspection value
IWS	Institut für wassergefährdende Stoffe, Technical University of Berlin, Germany
KBS	Knowledge-based systems
K_d	Absorption coefficient
k_f	Permeability factor
K_H	Henry's Law constant
$KMnO_4$	Potassium permanganate
K_{OC}	Sorption coefficient
L	Litre
LFA	Logical Framework Approach
LNAPL	Light Non-Aqueous Phase Liquid
LogFrame	Logical Framework Matrix
L/S	Liquid to soil ratio
LTTD	Low temperature thermal desorption
m	Meter
m³	Cubic meter
m_I	Multiplicator 'influence of discharge' condition according to Baden-Württemberg model

m_{II}	Multiplicator 'input' condition according to Baden-Württemberg model
m_{III}	Multiplicator 'transport and effect' condition according to Baden-Württemberg model
m_{DS}	Mass of dry substance in landfill-sector with base area
mg/L	Milligrams per liter
Mh	Man hour
mm	Millimeter
$mmol_c$	Millimol cations
MAS	Mass waste landfill
MNA	Monitored natural attenuation
MS	Microsoft
MSP	Mechanical separation process
mV	Milli Volt
n	Total number of attributes in BSC
NA	Natural attenuation
NAPL	Nonaqueous phase liquids
ng	Nanogramm
n.i.	No information
N-Value	land use characteristics
ÖNORM	Austrian Norm
P	Phosphate
PAH	Polycyclic aromatic hydrocarbons
PCB	Polychlorinated biphenyl
PCDD/F	Polychlorinated dibenzodioxins and furans
PCP	Pentachlorophenol
pH	Acidity value
p_i	Points given to the attribute in BSC model
PR	Pollutants removal
PRB	Permeable Reactive Barriers
PTB	Pump & Treat + Bioremediation, Active measure technology
PTC	Pump & Treat + Chemical Remediation, Active measure technology
QA	Quality Assurance
Q_A	Water outflow from landfill body
Q_N	Precipitation water input into landfill body

Q_v	Water outflow from landfill body through evaporation and degradation losses
Q_Z	Groundwater inflow into landfill body
R	Risk
r_0	Material danger according to Baden-Württemberg model
R_0	Historical risk (1-2) according to EVAPASSOLD model
r_I	Discharge conditions according to Baden-Württemberg model
r_{II}	Input conditions according to Baden-Württemberg model
r_{III}	Transport and effect according to Baden-Württemberg model
RBC	rotating biological contactors
RES	Residual waste landfill
ROI	Radius of influence
RW	Reactive walls/Funnel and gate system
RWA	Reactive walls, Containment technology
S_0	Endangerment value (S-Value) posed by substances found in an evaluated old deposit/industrial site
SAG	Servicio Agrícola y Ganadero, Chile. Agriculture and Cattle Service
SAE	In-situ soil air extraction, Physical and chemical remediation technology
SAS	In-situ air sparging, Bioremediation technology
SEREMI	Servicio Regional Ministerial, Chile. Regional Ministry Service
SERNAGEOMIN	National Service on Geology and Mining, Chile
SLI	Slurry trench wall, Containment technology
SMA	Thin cut-off wall ,Containment technology
SMART	Simple multiattribute rating technique
SOL	Solidification stabilization, Containment technology
SPC	Sites Potentially Contaminated
S/S	Solidification/stablilization
S-Value	Material danger (endangerment class)
SVE	Soil vapor extraction
SVOC	Semivolatile organic compounds
SWA	Ex-situ soil washing, Physical and chemical remediation technology
TA	Technical assessment
TDE	In-situ thermal desorption, Thermal treatment technology
TE	Toxicity equivalent
THP	Thermal process

TOC	Total Organic Carbon
T.V.	Threshold value
µg/L	Micrograms per liter
U	Unknown data according to Baden-Württemberg model
$U(A_i)$	Utility function according to BSC
UFG	Austrian Law for the promotion of environmental measures (Umweltförderungsgesetz)
UMS	Sheet pile wall, Containment technology
USSR	Union of Soviet Socialist Republics
VOC	Volatile organic compounds
V-Value	Location characteristics
VEB	Vertical engineered barrier
W	Weight in the BSC model
WE	Western Europe
WP	Washing process
WRG	Austrian Water act (Wasserrechtsgesetz)

7.3 Figures

7.4 Tables

Annex I: Legal framework for the management of contaminated sites in Europe, Austria and Chile

I.1 Summary of European legislation on contaminated sites

The following sections intend to clarify the legal framework for all EU member states when approaching the contaminated sites problem. Among many regulations, the most important directives at the EU-level are the EC directive on the quality of drinking water **Fehler! Verweisquelle konnte nicht gefunden werden.**],[243],**Fehler! Verweisquelle konnte nicht gefunden werden.**], and the water framework directive **Fehler! Verweisquelle konnte nicht gefunden werden.**],**Fehler! Verweisquelle konnte nicht gefunden werden.**], groundwater protection **Fehler! Verweisquelle konnte nicht gefunden werden.**], **Fehler! Verweisquelle konnte nicht gefunden werden.**].

European Council Directive on the quality of drinking water

The Directive's objective is to protect human health from adverse effects resulting from contamination of water intended for human consumption. It sets standards for water intended for drinking, cooking, food preparation or other domestic purposes, regardless of its origin and whether it is supplied from a distribution network, from a tanker, or in bottles or containers. The standards also apply to commercial premises and to water used in food production unless it cannot affect the wholesomeness of the foodstuff in its finished form.

The Directive sets parametric values for drinking water standards generally in line with the 1993 World Health Organization guidelines for drinking water quality. These guideline values represent the concentration of a constituent that does not result in any significant risk to the health of a consumer, usually over a lifetime of consumption. The most important change in the Directive is the reduction from 50 μg/L to 10 μg/L in the maximum permitted concentration of lead in drinking water. This change is introduced primarily in order to protect infants, young children and pregnant women from the neuro-toxic effects that are known to contribute to IQ deficits, learning and behavioral problems.

The value or concentration set for substances and parameters in the Directive incorporates margins that allow for uncertainties in the current estimation of risk. New parameters have been added where new scientific research has shown this to be necessary, but overall the total number of parameters has been reduced to include only those considered essential to ensure a continued high level of health protection. Member States are left to set values for additional national parameters where it is necessary, in light of local conditions, in order to protect human health.

Monitoring requirements are revised in the Directive, and allow Member States to adapt the amount and nature of monitoring to local conditions. The approach to reference methods of analysis for monitoring has also been revised to permit the use of methods meeting certain performance standards rather than requiring the use of certain defined methods. This allows

Member States to adapt their methods to technical and scientific progress without necessitating changes to the Directive.

The Directive provides a flexible framework of derogations within which Member States can redress failures to meet the required standards provided there is no potential danger to human health and that the supply of drinking water cannot be maintained by any other reasonable means.

The Water Framework Directive

The Water Framework Directive 2000/60/EC – "Establishing a framework for Community action in the field of water policy" was published in the European Union (EU) Official Journal in December 2000. The Directive is the most significant piece of European water legislation for over 20 years.

The aim of the Directive is to take a holistic approach to water management. It updates existing EU Water legislation through the introduction of a statutory system of analysis and planning based upon the river basin. The following are the key aims of this Directive:

- expanding the scope of water protection to all waters, surface waters and groundwater,
- achieving "good status" for all waters by a set deadline,
- water management based on river basins,
- "combined approach" of emission limit values and quality standards,
- getting the prices right,
- getting the citizen involved more closely,
- streamlining legislation.

Historically, there has been a dichotomy in approach to pollution control at European level, with some controls concentrating on what is achievable at source, through the application of technology; and some dealing with the needs of the receiving environment in the form of quality objectives. Each approach has potential flaws.

For this reason, a consensus has developed that both are needed in practice - a combined approach. The Water Framework Directive formalizes this. The framework comprises the development of a list of priority substances for action at EU level, prioritized on the basis of risk; and then the design of the most cost-effective set of measures to achieve load reduction of those substances, taking into account both product and process sources. On the effects side, it co-ordinates all the environmental objectives in existing legislation, and provides a new overall objective of good status for all waters, and requires that where the measures taken on the source side are not sufficient to achieve these objectives, additional ones are required.

All the elements of this analysis must be set out in a plan for the river basin. The plan is a detailed account of how the objectives set for the river basin (ecological status, quantitative status, chemical status and protected area objectives) are to be reached within the timescale required. The plan will include all the results of the above analysis: The river basin's characteristics, a review of the impact of human activity on the status of waters in the basin, estimation of the effect of existing legislation and the remaining "gap" to meeting these objectives, and a set of measures designed to fill the gap.

Directive on the protection of groundwater against pollution caused by certain dangerous substances

Existing EU groundwater policy, that is Directive 80/68/EEC **Fehler! Verweisquelle konnte nicht gefunden werden.**] on the protection of groundwater against pollution caused by certain dangerous substances, has been aimed at protecting groundwater from direct and indirect discharges of a number of pollutants. But this Directive does not set any clear quality objectives nor does it require comprehensive monitoring. As a result, there is not much data available about the quality of groundwater in Europe. The proposed Directive will change this situation.

With this proposal, the Commission has fulfilled an obligation under the Water Framework Directive, which aims to ensure good status of all waters in the EU. The Directive requires the Commission to propose specific measures to prevent and control groundwater pollution and achieve good groundwater chemical status. These measures have to include criteria for assessing the chemical status of groundwater and for identifying trends in pollution of groundwater bodies. The present proposal in addition introduces measures for protecting groundwater from indirect pollution (discharges of pollutants into groundwater after percolation through the ground or subsoil).

In the proposal, compliance with good chemical status is based on a comparison of monitoring data with quality standards existing in EU legislation on nitrates, plant protection and biocidal products, which set threshold values, i.e. maximum permissible concentrations, in groundwater for a number of pollutants.

In order to maintain control over indirect discharges of hazardous substances, the Commission's proposal makes provisions that will prohibit or limit such discharges. It includes quality objectives, so that the effects of the discharges can be monitored and future risks can be assessed.

The proposed Directive will ensure that ground water quality is monitored and evaluated across Europe in a harmonized way. The proposed approach to establishing quality criteria is both flexible and iterative, taking account of local characteristics and allowing for further improvements. It represents a proportionate and scientifically sound response to the requirements of the Water Framework Directive.

In 2012, a comprehensive programme of measures to prevent or limit pollution of water, including groundwater, will become operational under the Water Framework Directive.

Monitoring results obtained through the application of the proposed Directive on groundwater will be used to design the measures to prevent or limit pollution of groundwater.

Community guidelines on State aid for environmental protection

Goal of this guideline is to determine whether and under what conditions state aid may be regarded as necessary to ensure environmental protection and sustainable development without having disproportionate effects on competition and economic growth **Fehler! Verweisquelle konnte nicht gefunden werden.**].

The guidelines apply to aid to protect the environment in all sectors governed by the EC Treaty, including those subject to specific Community rules on state aid (steel processing, shipbuilding, motor vehicles, synthetic fibres, transport and fisheries), but excluding state aid for research and development, training aid and the area covered by the guidelines for state aid in the agricultural sector. However, the guidelines do apply to the fisheries and aquaculture sector. Aid to promote the execution of important projects of common European interest that are geared, by way of priority, to the environment and often have beneficial effects beyond the frontiers of the Member State or States concerned may be authorized under the derogation in Article 87(3)(b) of the EC Treaty **Fehler! Verweisquelle konnte nicht gefunden werden.**]. The guidelines recognize three main types of environmental aid, namely:

- operating aid to promote waste management and energy saving,
- aid for small and medium-sized enterprises (SMEs) for advisory/consultancy services in the environmental field,
- investment aid.

As there are different types of investment aid (e.g. transitional investment aid to help SMEs, investments in energy saving), the guidelines spell out for each type of aid the conditions and ceilings applicable:

- transitional investment aid to help SMEs adapt to new Community standards,
- investments in energy savings,
- aid for firms located in assisted regions,
- aid for SMEs,
- aid for the rehabilitation of polluted industrial sites,
- aid for the relocation of firms.

In order to enable the Commission to assess any substantial amounts of aid granted under authorized schemes and to decide whether such aid is compatible with the common market, any individual case of investment aid must be notified in advance to the Commission where the eligible costs exceed EUR 25 million and where the aid exceeds the gross grant equivalent of EUR 5 million **Fehler! Verweisquelle konnte nicht gefunden werden.**]. The guidelines lapse on 31 December 2007.

a) Directive of the European Parliament and of the Council on environmental liability with regard to the prevention and restoration of environmental damage (provisional version)

On 23 January 2002, the Commission adopted a proposal for a Directive of the European Parliament and of the Council on environmental liability **Fehler! Verweisquelle konnte nicht gefunden werden.**] with regard to the prevention and restoration of environmental damage. In its Explanatory Memorandum the Commission sets out the reasons, including the economic rationale, why it considers the proposal justified. It is followed by a Business Impact Assessment form.

The evaluation sets out the key efficiency-related issues raised by the proposal: its benefits and costs, including the distribution of the costs and the expected impact on industry competitiveness, the effect on prevention, the financial security underpinning potential liabilities and the assessment of natural resource damage **Fehler! Verweisquelle konnte nicht gefunden werden.**].

Despite the fact that insurance of environmental liability is not mandatory, the proposed directive recommends Member States to encourage the use by operators of any appropriate insurance or other forms of financial security **Fehler! Verweisquelle konnte nicht gefunden werden.**].

b) Biodiversity Action Plan for the Conservation of Natural Resources

Improving or maintaining the status of wild flora and fauna and their ecosystems and habitats. Building on and complementing existing Community environmental legislation and initiatives and making maximum use of these instruments in order to put the objectives set out in the Community biodiversity strategy into practice **Fehler! Verweisquelle konnte nicht gefunden werden.**].

This communication is the second volume of the Commission Communication of 27 March 2001 on Biodiversity Action Plans in the areas of Conservation of Natural Resources, Agriculture, Fisheries, and Development and Economic Cooperation. This volume is specifically dedicated to the protection of natural resources **Fehler! Verweisquelle konnte nicht gefunden werden.**].

I.2 Summary of the Austrian legislation on contaminated sites

ALSAG – Law for the Clean-up of Contaminated Sites

The Law for the clean-up of contaminated sites provides the legal basis for the funding of the remediation of contaminated sites. It also contains regulations pertaining to the registration of suspected contaminated sites nationwide and to the assessment of the risk they present. The Federal Ministry for Agriculture and Forestry, Environment and Water Management is responsible for the enforcement of the Law for the clean-up of contaminated sites **Fehler! Verweisquelle konnte nicht gefunden werden.**].

a) Registration, investigation and assessment of suspected contaminated sites and contaminated sites

According to the legal stipulations, the governmental authorities of the federal provinces identify former waste disposal and industrial sites suspected to cause considerable environmental harm (suspected contaminated sites). The data thus gathered are submitted to the Federal Ministry for Agriculture and Forestry, Environment and Water Management and entered into the Register of Contaminated Sites by the Federal Environment Agency **Fehler! Verweisquelle konnte nicht gefunden werden.**].

Of the registered sites, the Federal Environment Agency identifies those presenting a major threat to human health or the environment on the basis of a risk assessment. The risk assessment is based on relevant investigations such as groundwater and soil analyses. If the investigations show a major environmental impact or threat, the suspected contaminated site is designated as a contaminated site and entered into the Register of contaminated sites. The urgency for carrying out remedial measures is expressed by three priority classes **Fehler! Verweisquelle konnte nicht gefunden werden.**]. A complete overview of the management procedure for contaminated sites can be observed in Figure I.1.

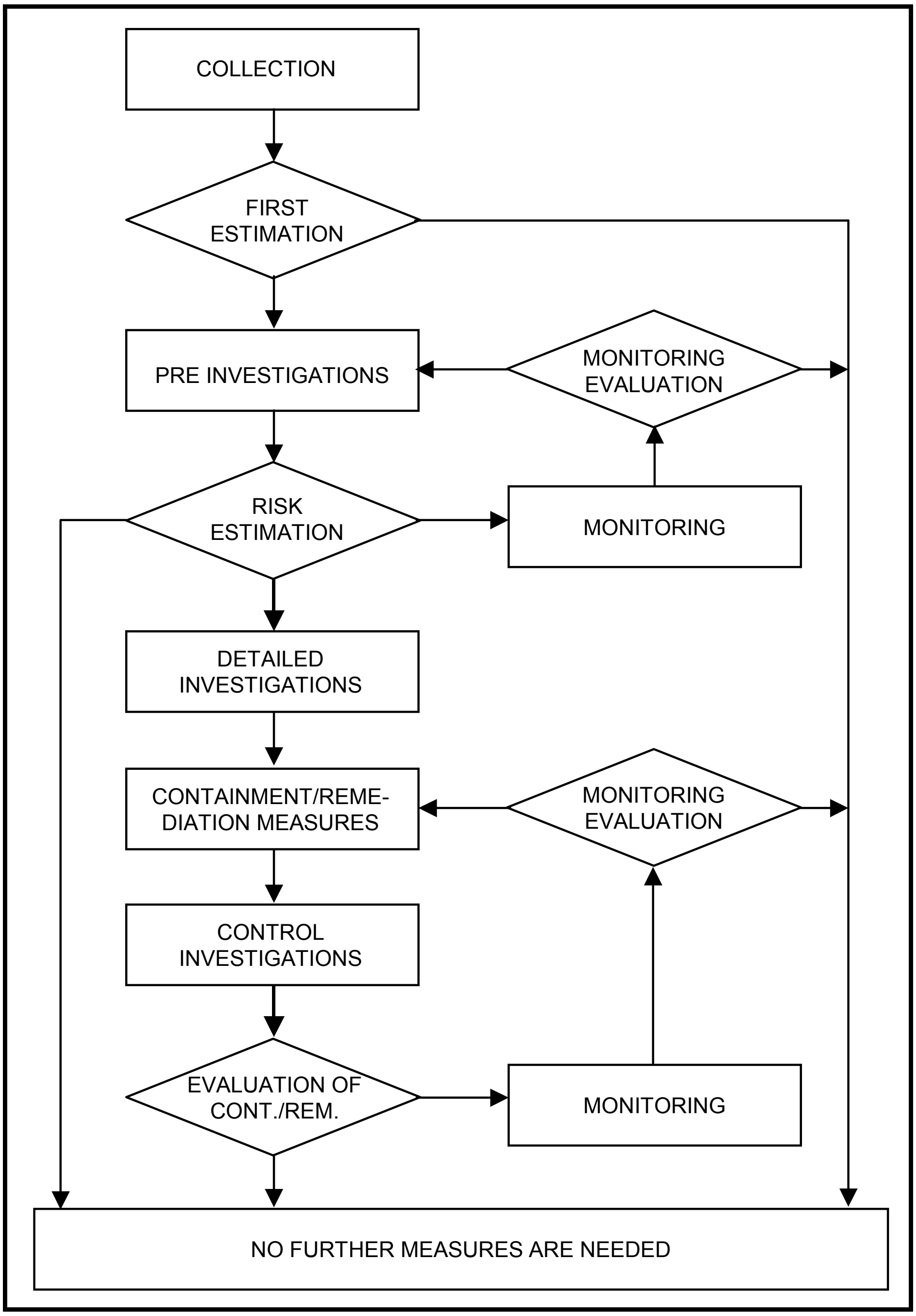

Figure I.1 Legal procedure for the management of (suspected) contaminated sites in Austria **Fehler! Verweisquelle konnte nicht gefunden werden.**]

b) Monitoring and control of containment / remediation measures

The success of the containment or remediation measures must be controlled. While in remediation cases the control procedure is closed after proof of its success, monitoring and control is permanently necessary in case of containment measures. For a correct progress control, targets are necessary for each individual environmental medium. These targets must be known already by the early phases of the containment or remediation measures. The methodology of the progress control must be co-ordinated with the containment or remediation methods and objectives.

The monitoring and control of success must be documented in a report. This report must contain the following data and evaluations:

- examination of the pollutant contents for each of the involved environmental media (soil, water, soil air) by chemical-analytic investigations of representative samples (in accordance with ÖNORM S 2087),
- an additional evaluation comparing this examination with the targets regarding their durability (in accordance with ÖNORM S 2088-1),
- description and evaluation of the containment or remediation measures regarding a total pollutant mass balance (e.g. migration into other environmental media, achieved pollutant elimination),
- recapitulatory evaluation of the efficiency of the selected procedures,
- all the documents for current control and documentation of the procedures (e.g. log book of operations, test certificates for construction and technical plants) must be attached to the report.

c) Contaminated sites fund – funding of remedial measures

The Law for the clean-up of contaminated sites stipulates that public funds shall be provided for the remediation of contaminated sites. The funds for the necessary measures are created through charges on the disposal and export of waste and its intermediate storage. From the total allocated funds 85 % are used to subsidize remedial measures at contaminated sites, and 15 % for the investigation of suspected contaminated sites requiring urgent attention **Fehler! Verweisquelle konnte nicht gefunden werden.**],[46].

Applications for the allocation of funds for remedial measures can be made by municipalities, municipal associations, waste associations, federal provinces, companies concerned with the remediation of contaminated sites, owners of contaminated sites or any other parties authorized to dispose of such properties. In principle, the objective of the Law for the promotion of environmental measures ("Umweltförderungsgesetz", the authoritative legal basis for the funding of activities aimed at the protection of the environment) is to subsidize measures for the remediation of contaminated sites in such a way that with the allocated funds a maximum ecological benefit is achieved while the costs remain within limits that are justifiable in terms of the economy as a whole **Fehler! Verweisquelle konnte nicht gefunden werden.**],[46].

ÖNORM S 2087: Contaminated sites – Identification and investigation of (suspected) contaminated sites

Through the identification and investigation of (suspected) contaminated sites it is possible to evaluate their hazardous potential. This norm provides an application-oriented overview of the most common investigation and research methods, and thus it serves as an efficient information provision as well as a basis for a proper comparability of the results.

The ÖNORM S 2087 should be used for the collection of information and at the planning and control stages of (suspected) contaminated sites investigations. Purpose of this ÖNORM is the definition of identification contents, the investigation goals as well as from investigation methods. Goal of the identification and investigation of (suspected) contaminated sites is to make information available for evaluation and in the consequence for planning and controlling of containment and remediation measures **Fehler! Verweisquelle konnte nicht gefunden werden.**].

ÖNORM S 2088-1: Contaminated sites – Risk assessment concerning the pollution of groundwater which is to be safeguarded

This ÖNORM shall be used during the evaluation of old deposits or industrial sites regarding groundwater endangerment. Purpose of this ÖNORM is to specify the bases for the evaluation of test results at old deposits or industrial locations as well as the estimation of the endangerment of the groundwater resulting from it. The orientation values indicated in this ÖNORM are the starting point for a location-referred evaluation of the individual case (e.g. specific soil chemistry). Goal of the evaluation of (suspected) contaminated sites is to determine the necessity for containment or remediation measures: It is vitally necessary to maintain clean groundwaters, as part of the natural water circulation and an important element of the ecosystem.

ÖNORM S 2088-2: Contaminated sites – Risk assessment for polluted soil concerning impacts on surface environments

The exposure to environmental as well as health endangerment materials in the past has caused a series of underground pollution. This ÖNORM describes the technical bases for the ecologically- necessary measures for their danger reduction and/or danger recovery.

The ÖNORM S 2088-2 shall be used during the evaluation of (suspected) contaminated sites regarding soil endangerment. Goal of this ÖNORM is to specify the bases for the evaluation of test results at (suspected) contaminated sites as well as the endangerment estimation of the soil resulting from it. Goal of the evaluation of (suspected) contaminated sites is to determine the necessity for containment or remediation measures. The maintenance of a clean soil as base of life for humans, animals and plants as well as a component of the ecosystem, in particular with its water and nutrient cycles, must be guaranteed on a long-term basis **Fehler! Verweisquelle konnte nicht gefunden werden.**].

ÖNORM S 2088-3: Contaminated sites – Part 3: Risk assessment for public asset air which is to be safeguarded

This standard describes the technical bases for the necessary measures for the danger reduction and/or danger recovery for the environment. This standard is to be applied during the evaluation of old deposits or old locations regarding air endangerment.

Purpose of this standard is it to specify the bases for the evaluation of air quality test results at old deposits or industrial locations as well as the estimation of the endangerment resulting from them.

ÖNORM S 2089: Contaminated sites - Security measures and remediation

This ÖNORM describes the up to date state-of-the-art processes for the containment and remediation of contaminated sites, providing instructions for their application as well. These procedures can be suitable for the containment and remediation of other contaminated areas and for the treatment of pollutant-loaded wastes, as well.

I.3 Chilean regulations related to contaminated sites

The following summary has been extracted from the Ph.D. work written by Navia [186].

General Norms regarding the protection of the national environment

They refer to the Political Constitution of the State, Organic Constitutional Laws, General Fundamentals in Environmental Issues, Navigation Law, Supreme Decreets, Law Decreets, Decreets with Law Force, Water Code, Sanitary Code and specific Resolutions.

a) Political Constitution

The Political Constitution of the State in its Article 19, Nr. 8, guarantees all the persons to "*live in an environment free of contamination*" and that is "*an obligation of the State to watch for this right not to be affected and to preserve the natural surroundings*".

b) Govern and Regional Administration Organic Constitutional Law Nr. 19.175

This law establishes that at a provincial level will exist a government that will be in charge of watching for the preservation and improvement of the environment.

c) Municipalities Organic Constitutional Law 18.695

Establishes the role of the municipalities in the application of legal norms and techniques for preventing the environmental deterioration (Art. Nr. 20).

d) Law Nr. 19.300 about General Fundamentals in Environmental Issues

This law, established in 1994, is aimed for establishing a sound relationship between economy, nature and the human population. It sets the base for a modern and realistic environmental management at a national level. In addition, the Environmental Impact Assessment System (SEIA) was introduced to implement the Law 19.300. The purpose of the SEIA, applied to projects and/or activities performed by the public and private sectors is to assure the environmental sustainability of said undertakings. The Law 19.300 provides that certain projects or activities capable to generate environmental impacts must be subjected to a SEIA. Their specific effects, characteristics or circumstances will determine if an Environmental Impact Statement or an Environmental Impact Study should be performed. The SEIA is to be conceptualized as a set of procedures designed to identify and evaluate positive and negative environmental impacts to be generated or presented by a given project or activity. The SEIA will assist in designing measures aimed for abating the negative impacts and enhancing any positive effects. An important part of these procedures depends on the involvement of State entities with environmental jurisdiction and/or in charge of issuing sectorial environmental permissions associated with the project or activity. The Law 19.300 has placed the burden of implementing and administrating the SEIA on the National Environmental Commission (CONAMA). Within this institutional framework, CONAMA and the Regional Environmental Commission (COREMA) are in charge of coordinating the process whereby ratings are assigned to the Environmental Impact Study and Environmental Impact Statements. The various different State bodies with environmental competences participate actively in this process.

e) Navigation Law, Law Decreet Nr. 2.222

In Article 142, it is prohibited to throw residues or to spread oil and derivates, mineral tailing pond waters and other hazardous materials that produce damage to the water bodies under national jurisdiction, in ports, lakes and rivers.

f) Supreme Decreet Nr.1 from the Ministry of Defense

This norm establishes the Regalement for the Control of the Aquatic Contamination, derived from the Navigation Law.

g) Resolution 12.600 from DIRECTEMAR

The resolution 12.600 of the General Administration of the Marine Territory and Merchant Navy (DIRECTEMAR) regulates the disposal of wastewaters into the juridical territory of this institution, namely seas and navigable continental water bodies.

h) Water Code

Under the ruling principles of the water code a great quantity of specific legal instructions of different origin and character are in force. Their objectives vary from funding of water-connected activities to control of emissions and the delivery of environmental quality norms. The total of the norms related to contamination is formed by 61 dispersed juridical texts: international agreements, laws, decrees and resolutions. These texts are primarily aimed for prohibiting contamination of maritime and continental water.

i) Drinking Water Law

The regulation of services for water destined for human consumption that was established in 1969; and lays down that water for human consumption may not contain elements, chemical substances, toxic or dangerous substances and pathogen organisms that possibly have not been eliminated by a common treatment in higher concentrations than the ones laid down. These waters also must be free of microscopic organisms and substances that can cause problems in the normal operation and efficiency of treatment processes. Furthermore, obligations for the drinking water providing enterprises are established in this law.

j) Chilean Norm for Potable Water

The Chilean Potable Water Norm defines the physical, chemical, radioactive and bacteriological requirements with that waters destined for human consumption have to comply. This norm is applicable to potable water from every source. The tables in this norm define the maximum acceptable limit for each type of contaminant (substance or element, chemical or radio-active matter) that the water may contain. In the case of bacteriological contaminations the norm requires that drinking water have to be totally free of microorganisms of faecal origin. Furthermore the norm establishes that the drinking water that is distributed by drinking water networks, has to be treated with a disinfection process that has a permanent effect. Chlorine, chlorinated compounds and iodine are authorized by the responsible Health Service. At the same time, the norm lays down that the minimum residual concentration of free chlorine has to be equal to or higher than 0,2 mg/L in every point of the net. No maximum concentration for free chlorine is set.

k) Law 3.133 about Neutralization of Liquid Industrial Wastes

This is the first legislative text of Chile that was aimed for the protection and conservation of the waters against the contamination by industries. It came into force in 1916. Since its creation in 1989 it is the responsibility of the SISS (Sanitary Service Office) to implement it. This law establishes the obligation of all industries to neutralize and purify their liquid industrial wastes that are disposed in aqueducts, watercourses, and catchment areas of rivers, lakes or ponds. It lays down that factories and metallurgical complexes that dispose their wastewaters in sewage systems have to submit these waters to a special neutralizing treatment so that the piping of the sewage systems is not damaged. The sanitary company that owns the sewage system where the wastewater is disposed has to control the compliance with the law. The SISS has to authorize the type of treatment and to supervise its correct function.

l) Supreme Decreet Nr. 351 from the Ministry of Public Building (MOP)

Establishes the prohibition of the discharge of industrial liquid wastewaters and other hazardous substances to the irrigation or the consumption in any pipeline, artificial or natural drain and sewage system.

m) Supreme Decreet Nr. 609/2000 from the Ministry of Public Building (MOP)

Is the emission norm for the regulation of contaminants associated with the disposal of liquid industrial wastewaters in the sewage system. It was elaborated and set into force in 1995 by the National Environmental Commission (CONAMA) in the implementation process of the Law 19.300 together with further emission norms and norms for environmental quality. This emission norm regulates the maximum quantity of contaminants that industries may feed into the public sewage systems. Its objective is to protect the sewage systems and networks of the enterprises that have to collect and dispose of their wastewaters, as well as protecting wastewater treatment plants and reducing eventual risks for the population.

n) Supreme Decreet Nr. 90/2000 from the Ministry of the General Secretary of the Presidency

On the 3rd of September 2001, the emission norm for the regulation of contaminants associated with the disposal of liquid industrial wastewaters into marine and superficial continental waters came into force. The aim of this norm is to prevent the contamination of these water bodies. It is applicable to all emitting entities – industrial as well as sanitary – that dispose their wastewaters into superficial water bodies (rivers, lakes, seas). For plants already existing when the norm came into force, the deadline for its implementation is established on the 3rd of September 2006.

o) Supreme Decreet Nr. 46/2002

It is the emission norm for the regulation of contaminants to groundwater courses and bodies. It was elaborated by CONAMA and came into force in March 2002. Its objective is the prevention of contamination of groundwater bodies by the control of deposition of liquid industrial wastes that percolate into the water carrying layers. It determines the maximum allowed concentrations of the mentioned contaminants in the emitted liquid industrial waste that is emitted via the ground to the water carrying layers by operations that are aimed for the infiltration of these wastewaters. This norm does not touch infiltration due to irrigation.

p) Chilean Water Quality Norm 1.333, Decreet Nr. 867

The Ministry of Public Building (MOP) elaborated this quality norm. It establishes the quality requirements for water for different types of applications, e.g. drinking water for human consumption, drinking water for animal consumption, irrigation, recreation, and aquatic life.

q) Sanitary Code

Establishes in a general form that the Health Services are responsible for the approvement of projects related with any construction for the evacuation, treatment or disposal of wastewaters and industrial and mining solid wastes.

r) Resolution Nr. 5.081 from the SESMA

The Metropolitan Environmental Health Service (SESMA) established a system for the declaration of industrial solid wastes managed in the Metropolitan Region of Santiago.

s) Supreme Decreet Nr. 86 from the Ministry of Mining

Establishes the Regalement for the Construction and Operation of Tailing Ponds

t) Supreme Decreet Nr. 144 from the Ministry of Health

Establishes in its Article 10, that any "*gases, vapors, dust, emanations or contaminants of every nature*", produced by any industrial facility have to be collected and eliminated. In its Article 60 prohibits the incineration of wastes in the urban area of the cities.

u) Decreet with Law Force Nr. 34

Establishes the environmental legislation of the fishing industry and its derivates.

v) Supreme Decreet Nr. 474 from the Ministry of Foreign Relationships

International agreement for the prevention of seawater contamination by hydrocarbons.

w) Supreme Decreet Nr. 476 from the Ministry of Foreign Relationships

International agreement for the prevention of seawater contamination by residues and other wastes.

Chilean legal framework on municipal wastes

Correspond to Laws, Supreme Decreets and Resolutions that in general establish that the municipalities are the responsible organisms for the cleanliness of the cities.

a) Law Decreet Nr. 3.557

In Article 9, it is established that any owner of an urban or rural ground is obligated to destroy, treat or process any wastes or waste mixtures dangerous to the agriculture.

b) Resolution Nr. 2.444 from the Ministry of Health

Establishes the minimal sanitary norms regarding grounds, operation and abandonment of non-controlled landfills.

c) Resolution Nr. 07077/76 from the Ministry of Health

Prohibits the incineration of municipal and industrial solid wastes in several communes of the Metropolitan Region and also prohibits the accidental or deliberated incineration in non-controlled landfills. In addition, obligates the industries that generate wastes to adopt the necessary measurements for the treatment (excluding incineration) and/or disposal.

Chilean legal framework on hazardous wastes

- Supreme Decreet Nr.1 from the Ministry of Defense (see General Norms)
- Law Decreet Nr. 3.557 (see Municipal Wastes)
- Sanitary Code (see General Norms)

a) Supreme Decreet Nr. 685 from the Ministry of Foreign Relationships

Establishes the “Basel Agreement about the Control of Movements of Hazardous Wastes and their Elimination”.

b) Resolution Nr. 3.276/77 from the Ministry of Health

Establishes the norm for the transportation of organic residues from the food industry and that can be used in animals growing farms. It also specifies the kind of vehicles and storage to be used for the transportation.

c) Decreet Nr. 298 from the Ministry of Transport and Telecommunications

It rules the transportation of hazardous cargos through the streets and gives some guidelines for the transference and transport operations

Annex II: Summary of the European contaminated sites situation

Table II.1. Dimension of the potentially and definitively contaminated sites in selected European Countries (adapted from [23],[36],[30]).

Country	Potentially Contaminated Sites				Contaminated Sites	
	Industrial	Waste	Identified	Estimated	Identified	Estimated
Albania	n.i.	n.i.	n.i.	n.i.	78	n.i
Austria	33,549	4,634	38,183	70,000	163	1,500
Belgium	n.i.	n.i.	5,528	9,000	7,870	n.i.
Denmark	n.i.	n.i.	37,000	40,000	3,673	14,000
Estonia	n.i.	n.i.	755	n.i.	n.i.	n.i.
Finland	n.i.	n.i.	10,396	25,000	1,200	n.i.
France	n.i.	n.i.	n.i.	800,000	896	n.i.
Germany	259,883	100,129	362,689	n.i.	n.i.	n.i.
Hungary	n.i.	n.i.	n.i.	n.i.	600	10,000
Iceland	n.i.	n.i.	n.i.	400	2	n.i.
Ireland	n.i.	n.i.	n.i.	2,000	n.i.	n.i.
Italy	n.i.	n.i.	8,873	n.i.	1,251	n.i.
Lithuania	n.i.	n.i.	1,700	n.i.	n.i.	n.i.
Luxembourg	n.i.	n.i.	616	n.i.	175	n.i.
Netherlands	n.i.	n.i.	n.i.	120,000	n.i.	n.i.
Norway	n.i.	n.i.	2,121	n.i.	n.i.	n.i.
Spain	n.i.	n.i.	4,902	n.i.	370	n.i.
Sweden	n.i.	n.i.	7,000	n.i.	12,000	22,000
Switzerland	n.i.	n.i.	35,000	50,000	3,500	n.i
United Kingdom	n.i.	n.i.	n.i.	100,000	n.i.	10,000
TOTAL	**-**	**-**	**514,763**	**1,216,400**	**31,776**	**57,500**

n.i.: no information

Table II.2. To-date known dimension of the contaminated sites situation in individual European countries [23],[30],[31],[36],[37],[38],**Fehler! Verweisquelle konnte nicht gefunden werden.**]

Country	Total Surface (km^2)	Potentially contaminated sites	Number of contaminated sites	Extension of Contaminated area (ha)	Remarks
Albania			78		
Austria	83,850	70,000	1,500		38,183 registered / 70,000 estimated potentially contaminated sites; 163 registered / 1,500 estimated contaminated sites
Belarus	207,600			4,600,000	**Chernobyl NPP:** 46450 km^2 (23% of the territory) contaminated by caesium-137; 21,000 km^2 (10%) by strontium-90; 4,000 km^2 (2%) by plutonium-238,239,240
Belgium	30,518	5,528	7,870		
Bulgaria	110994		275	7,400	
Denmark	43,090	30,000	4,520		14,000 sites are estimated to be contaminated
Finland	338,130	10,396			16% scrap yards and repair shops; 16% landfills and mine tailings; 10% saw mills and wood impregnation; 8% gasoline and service stations; 6% metal industry; 5% wastewater treatment plants; 5% concrete industry; 34%Others
France	551,500	896			
Germany	356,910	420,910			90,517 abandoned waste sites; 112,368 abandoned industrial sites; 202,885 abandoned former armament production sites; 3,240 abandoned military sites
Greece	131,957	5,000			
Italy	301,270	10,000			
Hungary	93,030	600	173		
Latvia	64,589	111			13% waste sites; 51% industrial sites; 3% military sites; 7% diffuse contamination
Lithuania	65,300	4,430			787 municipal landfills; 900 fertilisers and pesticides storage sites; 2,743 contaminated areas

Table II.2. To-date known dimension of the contaminated sites situation in individual European countries [23],[30],[31],[36],[37],[38],**Fehler! Verweisquelle konnte nicht gefunden werden.**]

Country	Total Surface (km^2)	Potentially contaminated sites	Number of contaminated sites	Extension of Contaminated area (ha)	Remarks
Luxembourg	2,582	616			
Netherlands	37,330	110,000			234 abandoned gasworks; 3300 municipal waste disposals; 80,000 abandoned industrials sites; 25,000 operating industrial sites; 6,200 out-of-service petrol stations; 2,500 military sites; others (waste disposals, diffuse sources, leakage in sewing systems and underground tanks)
Norway	323,900	2,500			
Poland	312,685			850,000	wastelands take some 3.3% country surface; chemically contaminated lands 2.7% - 56 military sites
Portugal	92,390	300			
Romania	238,391	1,634		164,000	
Slovakia	49,036	6,370			
Slovenia	20,256				
Spain	504,780	18,000			
Sweden	449,960	7,000	2,000		
Switzerland	41,290	36,000			
United Kingdom	244,880	100,000		200,000	25,000 abandoned waste disposal sites; 5,000 communal sites of gasworks; several 10,000 petrol filling stations; some hundred steelworks sites

(*) For Bosnia, Estonia, Iceland, Ireland, Liechtenstein, Macedonia and Russia there was either no reliable information or no information at all.

Annex III: Risk assessment for contaminated sites – Facts and figures

Table III.1. Industrial activities and their associated danger [44],[45].

Industrial activity	Associated danger
Agriculture	Burial of diseased livestock
Extractive industry	Extracting, handling and strorage of carbonaceous materials such as coal, lignite, petroleum, natural gas, or bituminous shale
Production of metals and their products	Production, refining or recovery of metals by physical, chemical, thermal or electrolytic or other extraction processes
Glass making and ceramics	Manufacture of glass and products based on glass. Manufacture of ceramics and products based on ceramics, including glazes and vitreous enamel
Production and use of chemicals	Production, refining, recovery or storage of petroleum or petrochemicals or their by-products, including tar and bitumen processes and the manufacture of asphalt
Engineering and manufacturing processes	Manufacture of metal goods, including mechanical engineering, industrial plant or steelwork, motor vehicles, ships, railways or tramway vehicles, aircraft, aerospace equipment or similar equipment. Storage, manufacture or testing of explosives, propellant ordnance, small arms or ammunition. Manufacture and repair of electrical and electronic components and equipment
Food processing industry	Manufacture of pet foods or animal feedstuffs. Processing of animal by-products (including rendering and maggot farming, but excluding slaughterhouses, butchering)
Paper, pulp and printing industry	Making of paper pulp, paper or board, or paper or board products, including printing and de-inking.
Timber and timber products	Chemical treatment and coating of timber and timber products
Textile industry	Tanning, dressing, fellmongering or other processes for preparing, treating or working leather. Fulling, bleaching, dyeing or other textile floor coverings (including linoleum works)
Rubber industry	Processing of natural or synthetic rubber (including tyre manufacturing or retreading)
Infrastructure	- Marshalling, dismantling, repairing or maintenance of railway rolling stock - Dismantling, repairing or rnaintenance of marine vessels, including hovercraft - Dismantling, repairing or maintenance of road transport or road haulage vehicles - Dismantling or maintenance of air or space transport systems
Water disposal	- Treating of sewage or other effluent - Storage, treatment or disposal of sludge including sludge from water treatrnent works - Treating, keeping, depositing or disposing of waste, including scrap (to include infilled canal basins, docks or rivercourse) - Storage or disposal of radioactive materials
Miscellaneous	- Premises housing dry cleaning operations - Laboratories for educational or research purposes - Demolition of buildings, plant or equipment used for any of the activities in the schedule

Table III.2. Environmental risk factors in contaminated sites [44]

Risk increasing	Risk reducing
Older Site	Younger Site
Process Industries	Service Industries
Owners/tenants without environmental management controls	Owners/tenants with environmental management controls
Hazardous waste produced	Low waste production, particularly if non-hazardous waste produced
Lack of knowledge of drainage system	Well understood and controlled drainage system
Low standards of bulk liquid containment	High standards of bulk liquid containment
Evidence of land contamination or contaminative uses	No evidence of contamination or contaminative uses
Sensitive or potentially polluting neighbours	Non-sensitive or benign neighbours
Proximity of and discharges to watercourses	Absence of sensitive neighbouring watercourses
Poor housekeeping	Good housekeeping
Complaints, warnings or prosecutions	No compliance or nuisance issues
Risk-increasing geology and hydrogeology	Impermeable soils and no sensitive aquifers

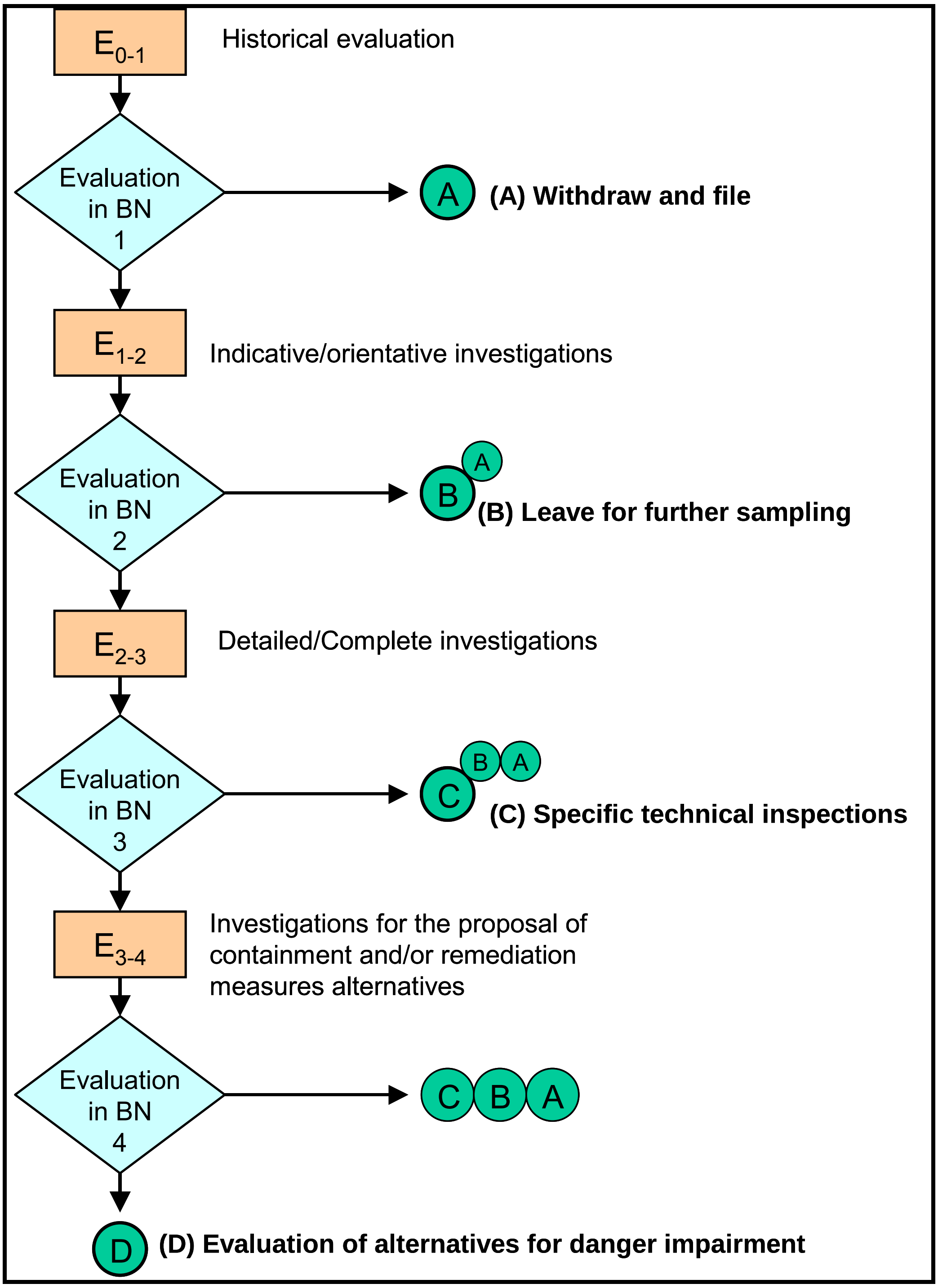

Figure III.1. Flow diagram of the Baden-Württemberg investigation and evaluation procedure

Annex IV: Considerations on the use of technological alternatives for contaminated sites management

Table IV.1. Considerations in the use of slurry walls, grout curtains and sheet pile walls [80].

Site condition	Slurry walls	Grout curtains	Sheet pile walls
Depth to impermeable layer	< 20 m [(a)]	Any depth	< 20 m (may go deeper with special equipment)
Hydrogeology	Any situation up to maximum length	Any situation. Grout can be injected only in key geological formations if desired	Any situation up to maximum length
Geology/ Geomorphology	Trenching difficult in bedrock and some soils	Grout will only fill void spaces of certain soil types. Grout will incre-ase strength of soft soils	Driving piles not possible through rock. Very soft soils may need extra support.
Type of contamination	Must choose slurry compatible with contaminants.	Must choose grout compatible with contaminants.	Some contaminants may corrode steel. Can apply special coating on steel.
Groundwater situation after implementation	Groundwater will flow around and/or under barrier. Modelling must be done to determine paths and flowrates. In some cases groundwater will “mound” behind the barrier. Existing extraction wells may be impacted.		
Surface conditions	Must be able to bring construction equipment to site. May need surface control of site after installation.		
Surface infiltration	A cap should be used to prevent infiltration inside after barrier walls. Alternatively a system of drains under the contaminated zone can collect infiltration and pump it for treatment.		

(a) According to the experience in Austria

Table IV.2. Comparative evaluation of slurry walls, grout curtains and sheet pile walls [80].

Factor	Slurry walls	Grout curtains	Sheet pile walls
Cost	Cheaper than grout curtains and sheet piles for depths up to 10 m.	Cheaper than sheet piles	Expensive if special driving techniques or heavy gauge seel are required.
Environmental concerns	Slurry material must be approved by regulator	Some grouts known for having toxicity. Must get regulator’s approval.	No concerns.
Longevity	May corrode or dissolve after 30-50 years. Solidified walls may crack.	Some grout will corrode or dissolve after 30 – 50 years.	May corrode under acidic conditions unless cathodic protection provided.
Effectiveness	100% effective initially if installed properly	Difficult to measure completeness of seal. Grout may not enter all pore spaces.	100% effective initially if installed properly
Depth to impermeable layer	10 m (up to 80 m [(a)])	Unlimited	20 m – 30 m [(a)]
Availability (ease of installation)	Trenching of about 5 m with standard construction equipment. Trenches to 10 m with specialized trenching systems with limited availability	Limited availability. Installation often difficult even for experienced installers.	Pile drivers and steel commonly available
Maintenance	Subsurface maintenance not possible. Must monitor to detect leaks. If leaks detected, must try to install secondary wall or excavate and re-do one section.		
Reversibility	Must be excavated	Usually not reversible	Piles may be removed and re-used

[(a)] According to the experience in Austria

Annex V: Second risk assessment module

This annex presents the different forms to be filled up by the end user in order to calculated the potential endangerment of the identified sites suspected of contamination. As it may be observed, the forms are user-friendly and simple. This has been intentionally done, in order to allow all kinds of stakeholders and decision-makers to provide the information, not requiring of special help for these purposes.

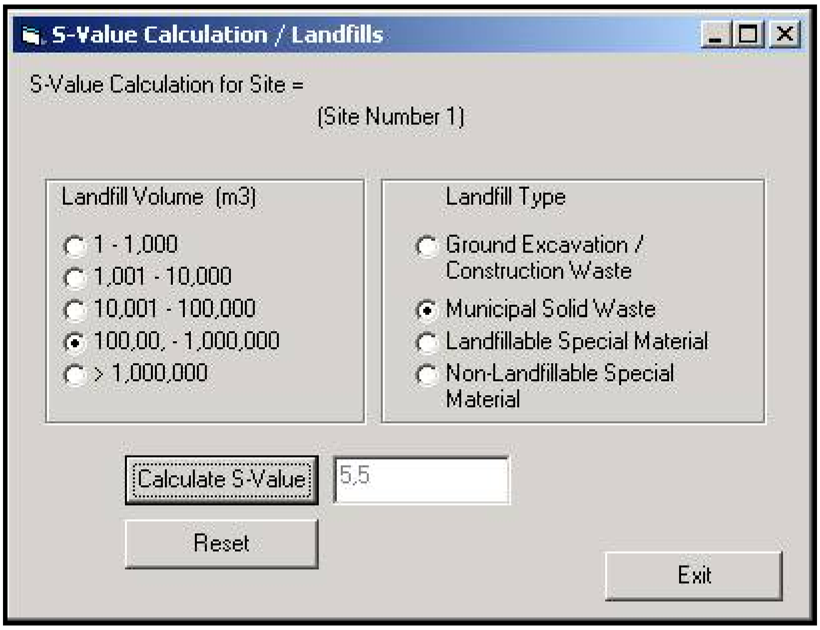

Figure V.1 Form for the calculation of the material danger for landfills

Figure V.2 First form for the calculation of the material danger for industrial sites.

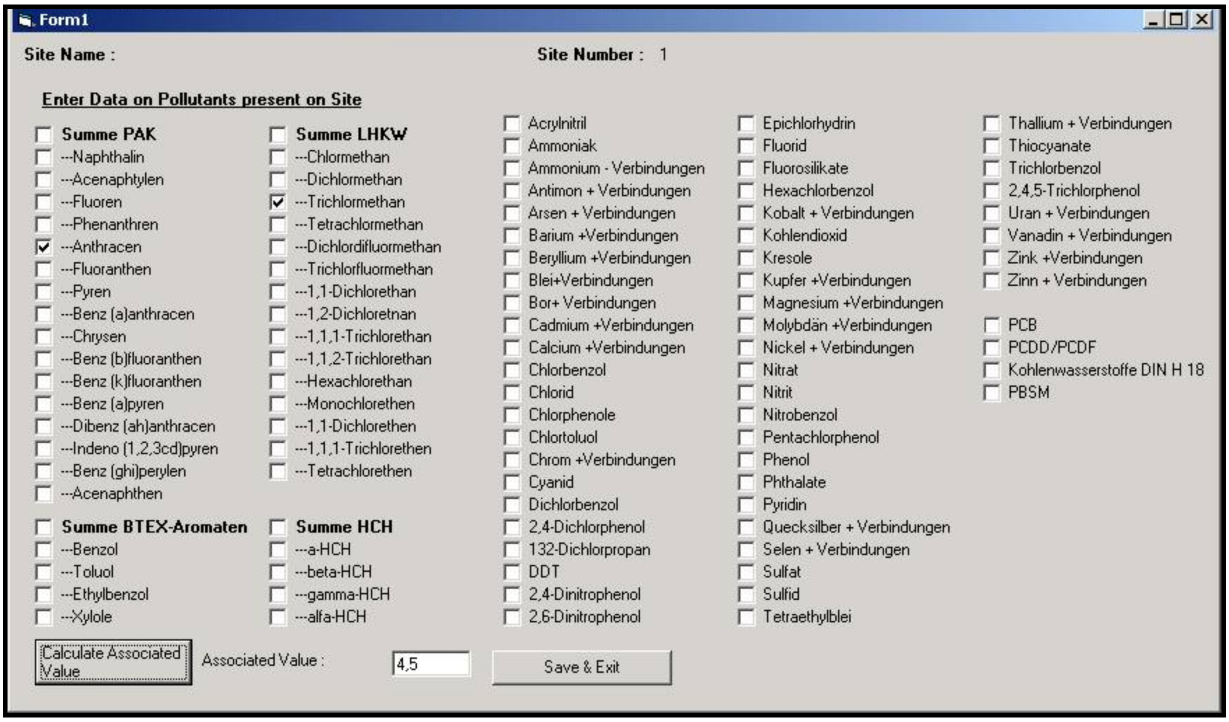

Figure V.3 Second form for the calculation of the material danger for industrial sites.

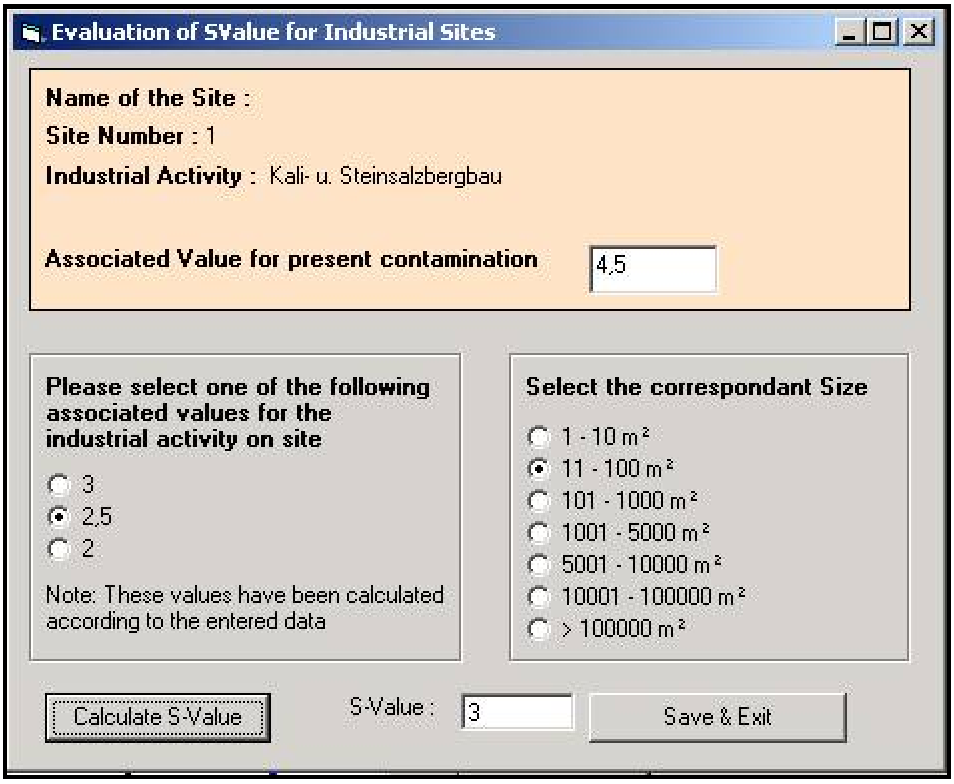

Figure V.4 Third form for the calculation of the material danger for industrial sites.

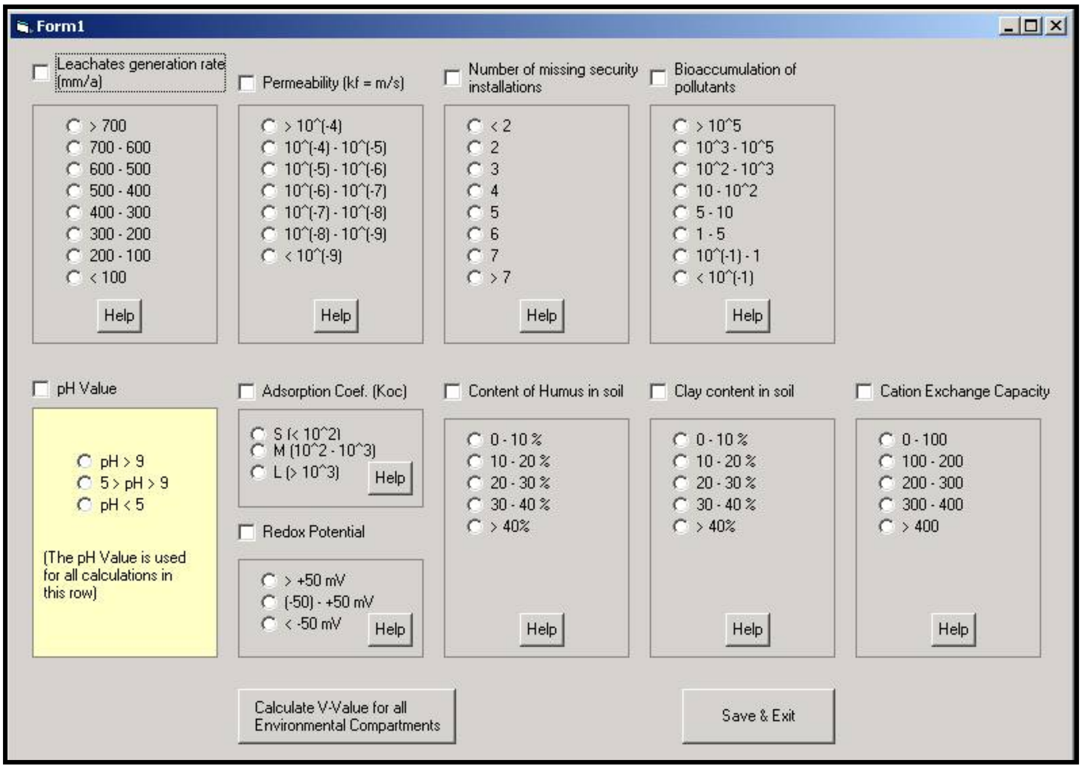

Figure V.5 Form for the calculation of V-Value.

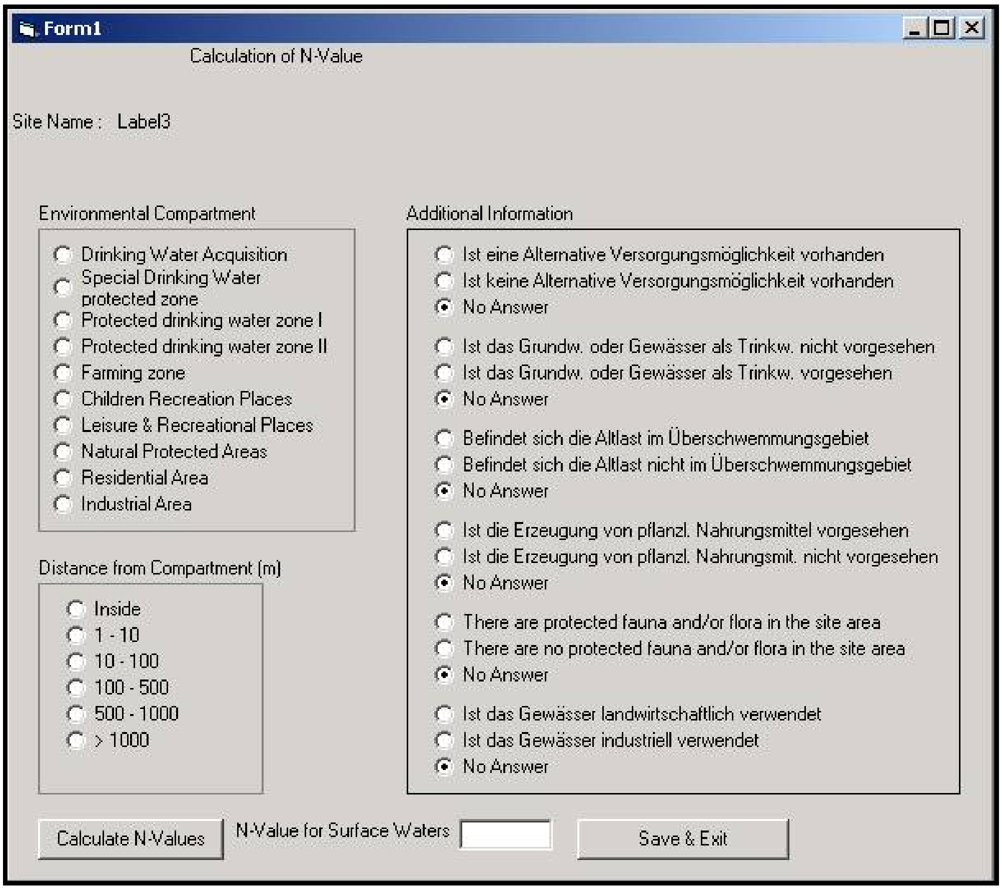

Figure V.6. Form for the calculation of the N-value.

Annex VI: Limits of contamination according to the land use of the site

Table VI.1. Place dependent remediation limits according to the Austrian legislation on polluted soil [209]

Substance	*Living places*		*Production places*	
	Inspection value [mg/kg d.s.]	Threshold value for actions [mg/kg d.s.]	Inspection value [mg/kg d.s.]	Threshold value for actions [mg/kg d.s.]
Inorganic Parameters				
Antimony	2	5	2	t.d.a.s.t.
Arsenic	20	50	20	t.d.a.s.t.
Lead	100	500	100	t.d.a.s.t.
Cadmium	2	10	1	t.d.a.s.t.
Chromium	50	250	100	t.d.a.s.t.
Copper	100	600	100	t.d.a.s.t.
Nickel	70	140	60	t.d.a.s.t.
Mercury	2	10	1	t.d.a.s.t.
Thallium	2	10	1	t.d.a.s.t.
Vanadium	-	-	50	t.d.a.s.t.
Zinc	-	-	300	t.d.a.s.t.
Cyanide Total	5	50	5	t.d.a.s.t.
Fluoride Total	200	1000	200	t.d.a.s.t.
Organic parameters				
Sum of HC	50	-	200	t.d.a.s.t.
PCDD/F (1)	10	100	10	t.d.a.s.t.
PCB	0.2	1	0.3	t.d.a.s.t.
Sum of PAH	1	50	1	t.d.a.s.t.
Benzo(a)pyren	0.5	5	-	t.d.a.s.t.

t.d.a.s.t.: to be determined according to soil type; d.s. = dry substance. (1) All values expressed in [mg/kg d.s.] except for PCDD/F in [ng TE/kg d.s.], Toxicity-Equivalent I-TEF. (2) Assay of individual cases necessary.

Table VI.1. Solids (total contents) and eluates based remediation limits according to the Austrian legislation on polluted groundwater assessment [210]

Substance	***Values for Eluates[mg/l]***				***Total content Values* [mg/kg$_{d.s.}$]**	
	I.V.		**T.V. for actions**		**I.V.**	**T.V. for actions**
	a	**b**	**a**	**b**		
Nitrate	30	50	(1)	(1)	-	-
Nitrite	0.1	0.5	1.0	(2)	-	-
Ammonium	0.5	2.0	5.0	(2)	-	-
Chloride	200	(1)	(1)	(2)	-	-
Sulfate	250	(1)	(1)	(1)	-	-
Phosphate as P	0.5	2.0	2.0	5.0	-	-
AOX as Cl	0.01	0.05	-	-	-	-
COD	20	40	50	80	-	-
Sum of HC	0.1	0.5	0.5	(2)	500	1000
Cyanide Total	0.05	0.1	0.5	(2)	25	250
Fluoride Total	1.5	3.0	5.0	(2)	500	3000
Aluminium	0.2	2.0	10.0	(2)	-	-
Arsenic	0.05	0.1	0.1	(2)	40	100
Lead	0.05	0.1	0.5	(2)	100	1000
Cadmium	0.005	0.005	0.05	(2)	2	20
Chromium	0.05	0.1	1.0	(2)	100	600
Iron	1.0	2.0	2.0	20.0	-	-
Copper	0.1	1.0	1.0	(2)	100	1000
Manganese	0.1	1.0	1.0	10.0	-	-
Nickel	0.1	0.5	0.5	(2)	100	500
Mercury	0.001	0.002	0.005	(2)	2	20
Zinc	3.0	3.0	3.0	(2)	300	2000
Sum of BTX	0.03	0.05	0.1	(2)	10	30
Benzine	-	-	-	-	100	250
Benzol	0.001	0.003	0.01	(2)	0.5	3
Phenol index	0.01	0.1	0.1	1.0	10	25
Sum of PAH	0.002	0.002	0.003	(2)	10	100
Sum of PCB	0.000 05	0.000 1	0.000 2	(2)	1	10

I.V.: Inspection value. T.V.: Threshold value. a: water-legally particularly protected or water-economically meaning areas. b: rest of areas where no water use is accomplished. (1): To be determined individually. (2): No increse in respect to threshold value for actions “a”.

Table VI.1. Site specific remediation limits according to the German legislation on polluted soil assessment. Case of redevelopment projects in direct contact with persons, soil for agricultural crops and greenlands [211]

Substance	TYPE of SITE							
	Sites in direct contact with persons				Soil for agricultural crops			Greenlands
	Children playgrounds	Residential areas	Parks and recreational zones	Industrial / Commercial areas	Inspection value (growth)	Inspection value (quality)	Threshold value for actions	
Inorganic Parameters								
Arsenic	25	50	125	140	0.4	200	-	50
Lead	200	400	1000	2000	-	0.1	-	1200
Cadmium	10	20	50	60	-		0.04 and/or 0.1	20
Chromium	200	400	1000	1000	-	-	-	-
Copper	-	-	-	-	1	-	-	1300
Nickel	70	140	350	900	1.5	-	-	1900
Mercury	10	20	50	80	-	5	-	2
Cyanide Total	50	50	50	100	-	-	-	-
Thallium	-	-	-	-	-	0.1	-	15
Zinc	-	-	-	-	2	-	-	-
Organic Parameters								
PCDD/F [1]	100	1000	1000	10000	-	-	-	-
PCB	0.4	0.8	2	40	-	-	-	0.2
Benzopyren	2	4	10	12	-	1	-	-
Hexachlorbenzol	4	8	20	200	-	-	-	-

[1] All values expressed in (mg/kg d.s.) except for PCDD/F in (ng TE/kg d.s.)

Annex VII: Definitions of indicators for the use of the balanced scorecard in contaminated sites management

Table VII.1. Required parameters for the definition of the selected indicators

IDENTIFI-CATION	**ID (Identity code)**	I01	Comments
	Indicator long name	Environmental burden of the technology	
	Indicator short name	Environmental burden	
DESCRIPTION	**Unit**	dml	
	Description of unit	Dimensionless	description
	Supported Sub-goal	1. Environment	name of the goal as well. Enough to say maybe only if it is economic, social, env. Or technology related
	Provided by	BP	Definition of the provider
	Relevance/Purpose of the indicator		why is it used, applied?. E.g. Env. Burden is a factor must be implemented within projects aiming to achieve sustainabilityAlso the policy (laws, regulations) MUST be implemented
	Art of the indicator		it can be limit value (e.g. nuisance), trend indicator (e.g. cost) or to compare "ist/soll" situation (e.g. sustainability, competitiveness, env. burdan)
	Temporal/spatial level		What is the present and future temporal/spatial level of indicator. E.g. Regional or national level, long term effect (15 years) or short term effect (1 year..) maybe the duration of the effect.
	Relationship to other indicators/goals		what is the positioning of this indicator to others?
CALCULATION	**Value of indicator**	calculated	measured or calculated or statistic. Base year.
	Description of calculaton		description of data needed, used and the algorythm applied
	Value to be achieved		what is the value u want to achieve (very good, good, etc.) depends on stakeholder and scenarios
	Limitation		is there any reason of measure/gather/process the value of indicator?
CALIBRATION	**Minimum value of indicator**		What is the possible minimum value of the indicator. Based on historical data and assupmtion/estimation for the future. Data used from other regions.
	Maximum value of indicator		What is the possible maximum value of the indicator. Based on historical data and assupmtion/estumation for the future
	Minimum Score of indicator		What is the score of the minimum value of indicator (0)
	Maximum Score of indicator		What is the score of the maximum value of indicator (10)
	K.O. Criteria		if there is, what is the value from what it cannot be less or more. E.g. nuisance is limited
	Utility function	linear	Linear; Quadratic; Cubic increasing; Cubic decreasing; and Square root,
WEIGH	**Indicator absolute weight**		given by the user (dm, stakeholder)
	Indicator relative weight		calculated based on the goa system and subgoal weights and ind. Absolute weight
OTHER	**Quality of data**		which data have been measured/calculated/estimated. Kind of sensitivity analyse of indicators
	Diagram/map		diagrams (historical data) or map to show the indicator over time and/or the geographical distribution of it
	References		References, sources used

Annex VIII: Site description of the study case for the validation of the developed knowledge-based system

South of Korneuburg (Lower Austria), an oil refinery was operated from 1923 to 1961. The former refinery area is located directly north to the highway exit Korneuburg between the northwest motorway and the federal highway 3. Plant operators were among others: from 1938 to 1945 the German Gasoline Corporation (Deutsche Gasolin Aktiengesellschaft), from 1945 to 1955 the Soviet Mineral Oil Administration in Austria (Sowjetische Mineralölverwaltung in Österreich) and from 1956 to 1961 the Austrian Mineral Oil Administration AG (Österreichische Mineralölverwaltung AG). In the operational facilities, crude oil was processed to gasoline, as well as petroleum, gas oils, oil distillates, bitumen, oil refines and fuel oils. The site is located in the Korneuburger basin, inside the basin-like extension of the Danube valley between the Danube breakthroughs, the "Korneuburger gate" (Leobendorf) and the "Viennese gate" (south of Korneuburg).

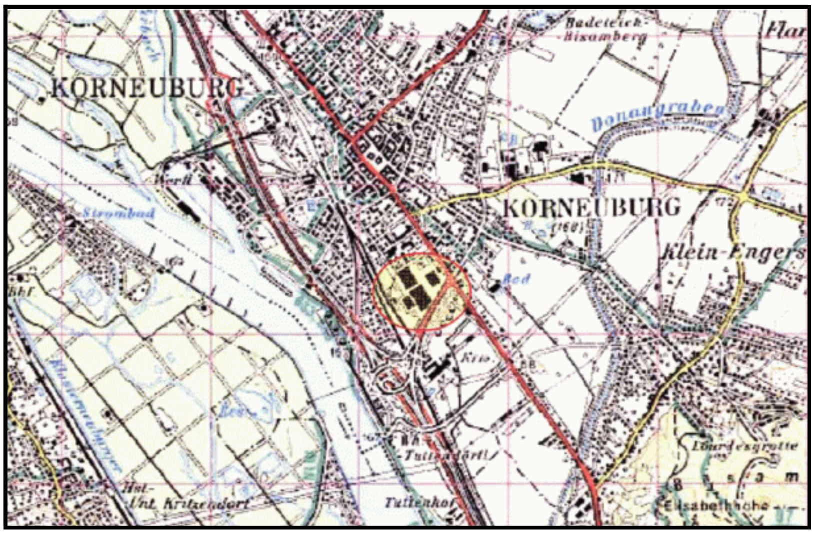

Figure VIII.1. Location of the study case

The main aquifer in the area flows through alluvial gravel from the Danube, being significantly influenced by it. At the “Korneuburg gate”, a supply from the Danube takes place; in contrast, at the "Viennese gate" as well as the in the area of "Tuttendorfer Breite" the groundwater has given a riverse flow to the Danube. The area of the old location has an elevation of 166m to 167m. The aquifer is overlaid by a strong surface layer of 1.5m to 5m of fine-grained sediments (clayey sand to sandy clay/tone). The sandy gravel of the aquifer posses an average thickness of 8m and a permeability value (k_f) between $9 \cdot 10^{-4}$ m/s and $2 \cdot 10^{-2}$ m/s refers to very good permeability. The groundwater stower is conformed on tertiary sand and clay. The upper edge of the confining soil layer has an elevation of 156m.

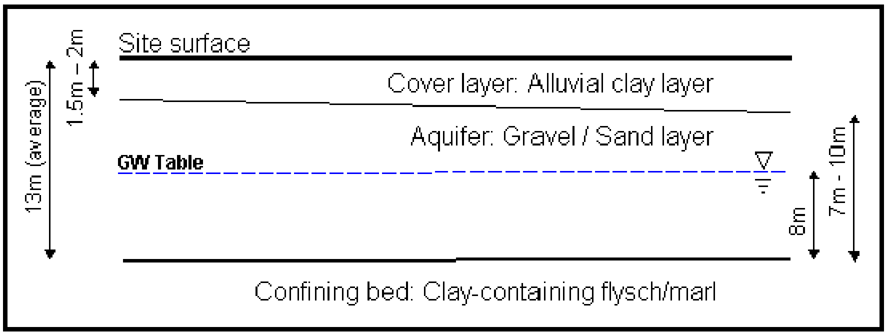

Figure VIII.2. Geological profile in the area of the former refinery

The former refinery area is about 500m East away from the Danube. The local groundwater flow conditions are affected by the water levels of the Danube. With low to medium flow conditions of the Danube is in principle given a groundwater flow directed southwest, i.e. in the direction of the Danube. The groundwater flow turns parallel to the stream axle with increasing proximity to the Danube. By higher discharges from the Danube, a reversal in the groundwater flow conditions is produced. The groundwater flow direction is re-arranged from, the Danube to the east. Under long-lasting Danube flood level conditions is the groundwater water level up to 167 m, and a flooding of the area in study is possible.

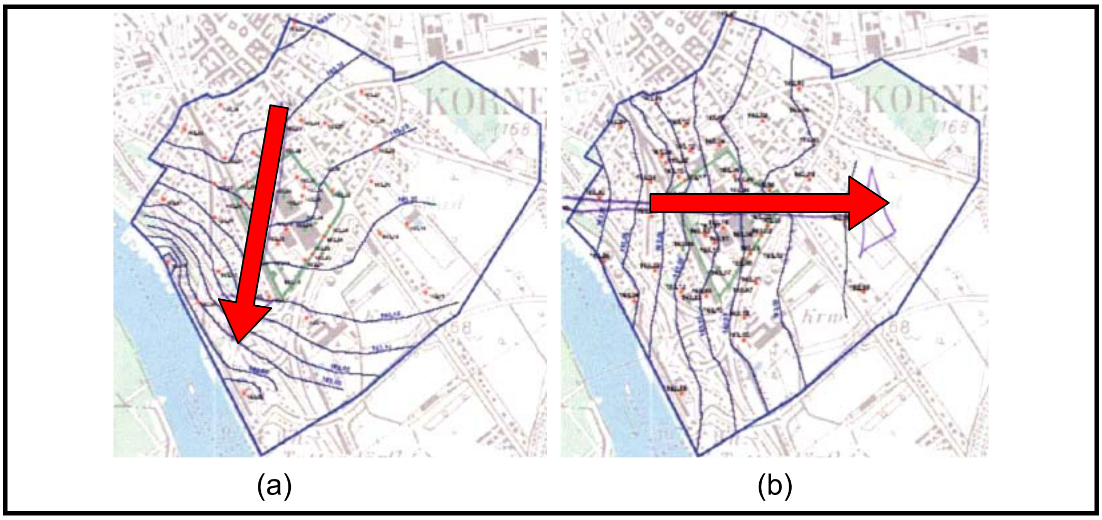

Figure VIII.3. Groundwater flow in (a) Normal conditions, and (b) Flooding conditions.

Qualitative impairments of the groundwater conditions within the range of this location have been documented ever since 1956. During the Second World War the facilities were partially destroyed. After the re-establishment of the facilities by the Soviet Mineral Oil Administration, the refinery continued to operate in 1960. In the summer of 1965, due to a long-lasting Danube flooding, an increase of the groundwater level over the site surface was observed. In the soil subsurface, existing mineral oil contamination was washed up by the groundwater, provoking wide oil impurities at the location's surface. At that time, house wells located northwest from the refinery area were also affected by oil leakages. Oil leakages can be regularly observed in the surroundings when the groundwater level arises. After closure of the refinery's production in 1973, almost the complete property remains fallow. Only in the northern part of the area, since the mid 70's, a couple of warehouses were erected. Nowadays, close to the site are found a populated area (north and west from the site), commercial areas (to the east) and an industrial area to the south, where the thermal power station Korneuburg operates. As far as the pollutants concentration is concerned, presents a profile of the sum of hydrocarbons present at different depths at the site. Moreover, Figure VIII.4 and Table VIII.1 introduce the summary of the estimated areas within the site and their contamination present.

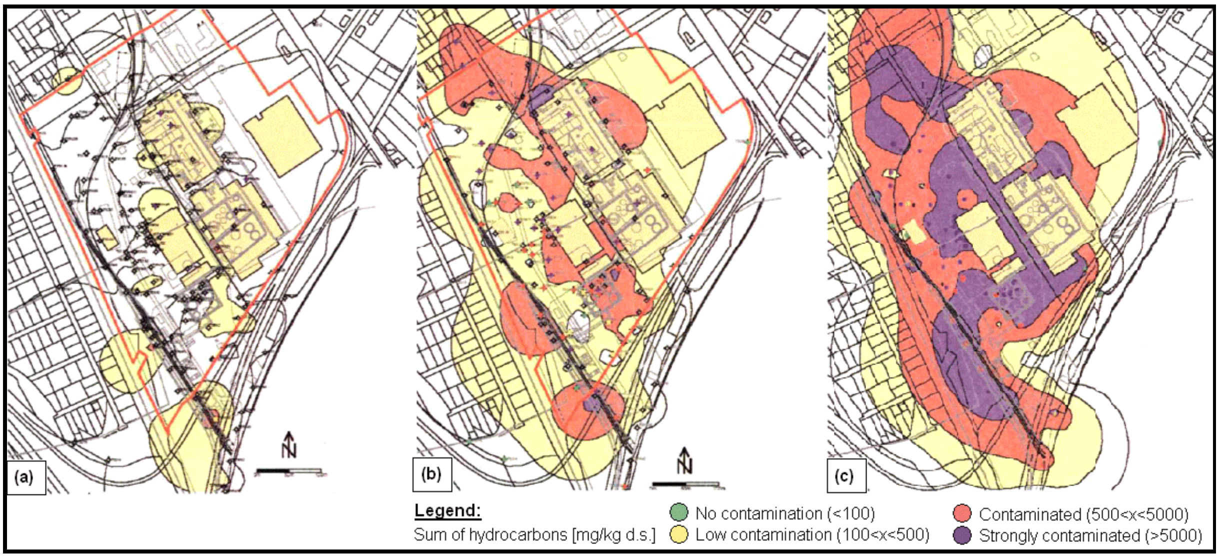

Figure VIII.4. Pollution distribution profile (sum of hydrocarbons) at the former refinery site: (a) at 0-2m from surface, (b) 2m-4m from surface, and (c) 4m-6m from surface

Table VIII.1. Minimum and maximun alternatives for the total contaminated soil mass estimation

Areal	Surface [m²]	Depth [m]	Mass [(a)] [Mg]	HC concentration [mg/kg d.s.]	Mass HC [Mg]
Minimum alternative					
Supply points	10,000	5.0	90,000	20,000	1,800
Central area	100,000	3.5	630,000	5,000	3,150
Periphery	80,000	2.0	290,000	2,500	725
				Total (minimum alternative)	**5,675**
Maximum alternative					
Supply points	10,000	5.0	90,000	50,000	4,500
Central area	100,000	4.0	720,000	7,5000	5,400
Periphery	80,000	2.0	290,000	3,000	1,100
				Total (maximum alternative)	**11,000**

[(a)] Utilizing an average soil density of 1800 Mg/m³

Annex IX: Identification of suspected areas in the Bio-Bio Region, Chile

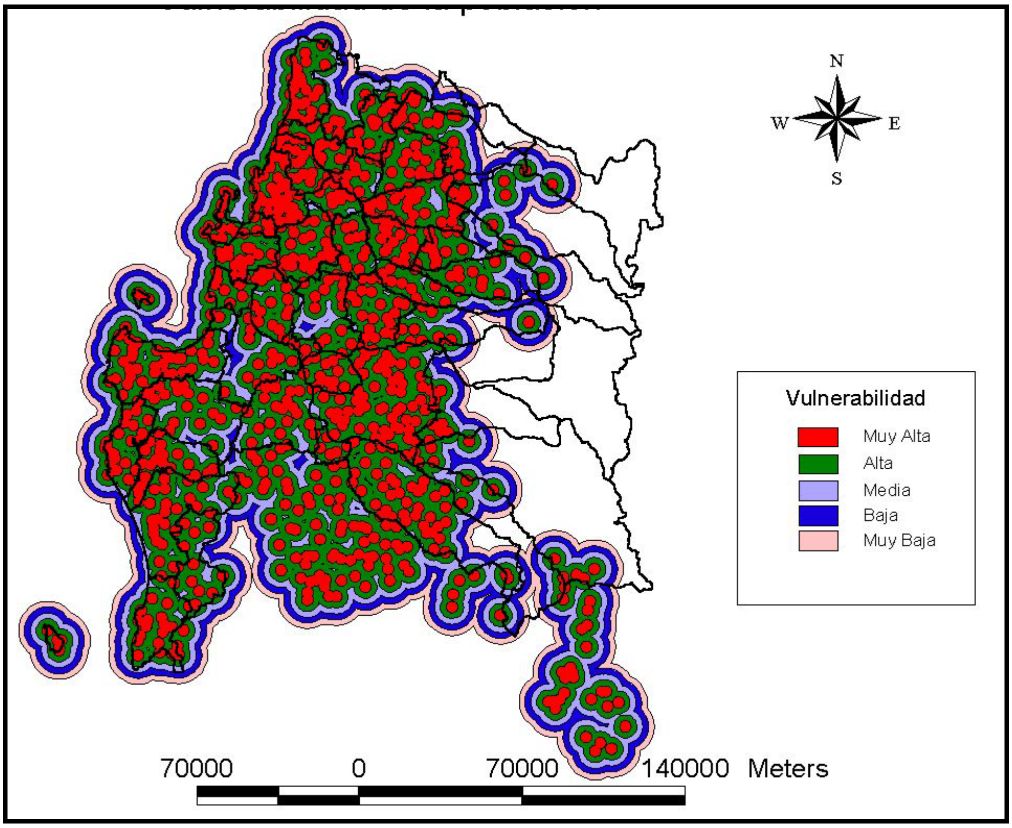

Figure IX.1. Vulnerability map for the population in the VIII region [257]

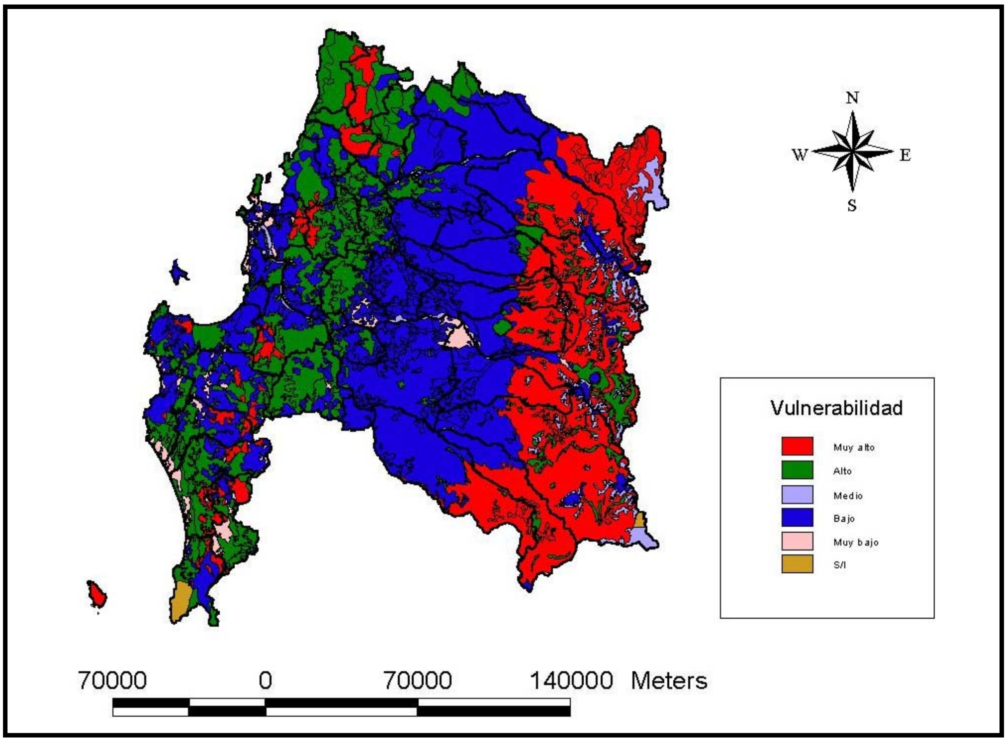

Figure IX.2. Vulnerability map for the biota in the VIII region [257]

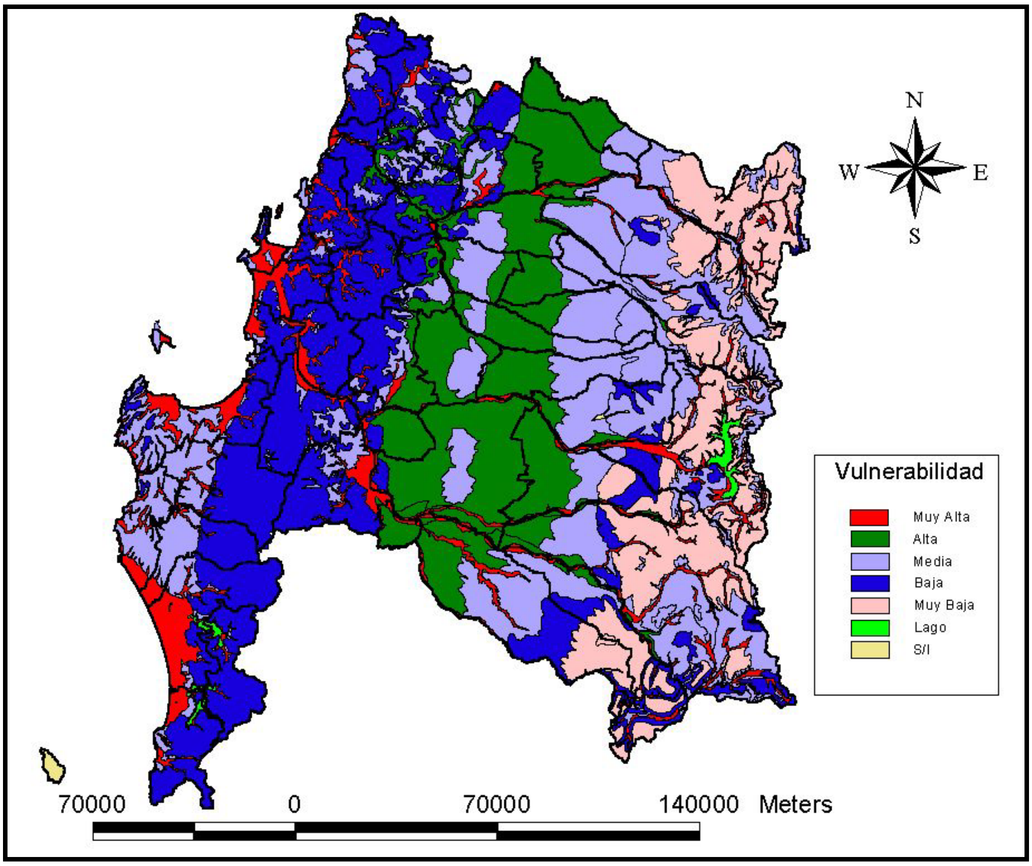

Figure IX.3. Vulnerability map for groundwater in the VIII region [257]

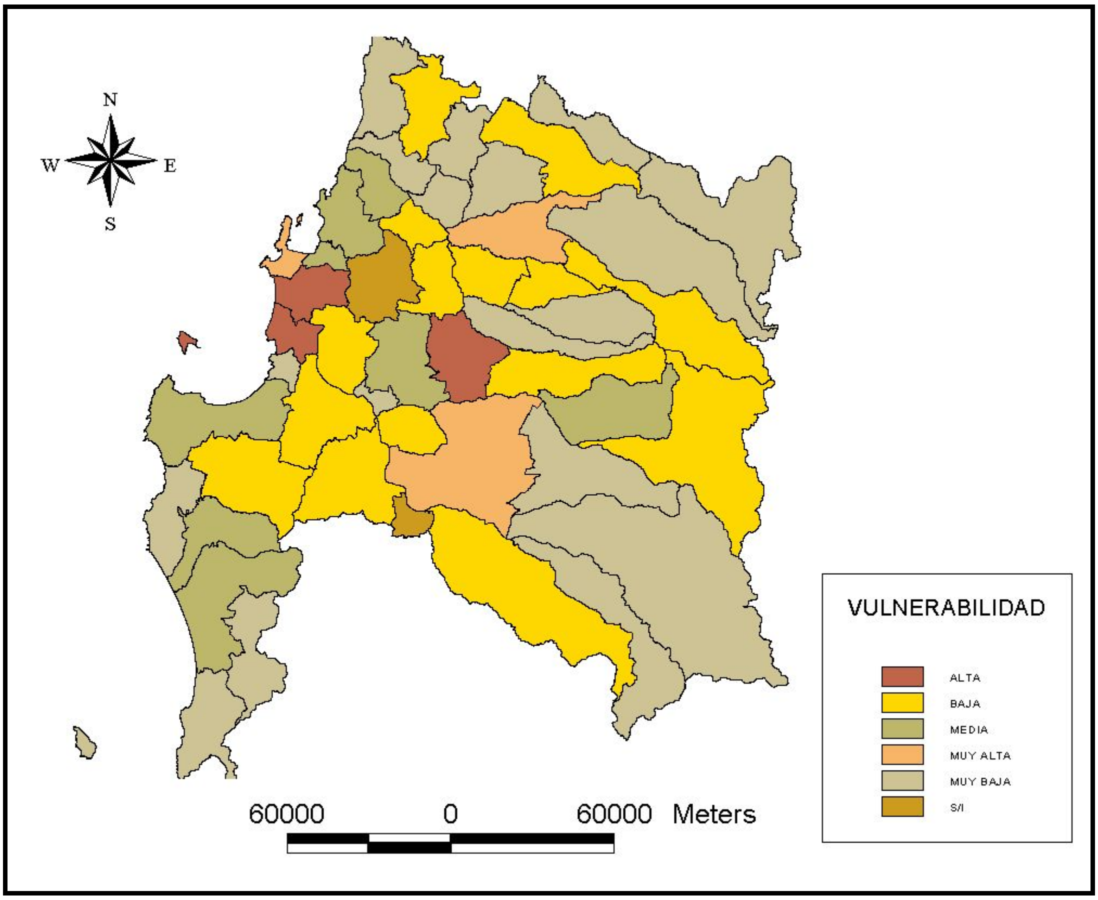

Figure IX.4. Final vulnerability map for the identification of the areas of interest in the VIII region of Chile [257]

Table IX.1. Overview of the companies associated to the studied industrial activities in the VIII Region, Chile [232].

Industrial activity	Associated companies	Province	Commune
Basic industry of steel	Compañía Siderúrgica Huchipato	Concepción	Talcahuano
Milk and milk products industry	Parmalat	Ñuble	Chillán
	Cecinas Chillán	Ñuble	Chillán
	Carnes Ñuble	Ñuble	Chillán
	Faenadora de Carnes Ñuble	Ñuble	Chillán
	Molino Fuentes	Ñuble	Chillán
	Mario Villablanca	Ñuble	Chillán
	Frisac	Ñuble	San Carlos
	Cecinas Pincheira	Ñuble	San Carlos
	Frigorífico Angus	Bio Bio	Los Angeles
	Nestlé	Bio Bio	Los Angeles
	Cecinas Naranjo	Bio Bio	Los Angeles
	Cecinas Fanda	Bio Bio	Los Angeles
	Cecinas Oriente	Bio Bio	Los Angeles
	Agroantuco	Bio Bio	Los Angeles
	Conservas Osiris	Bio Bio	Los Angeles
	Faena de Carnes Yumbel	Bio Bio	Yumbel
Packaging of marine products	Frigorífico Concepción	Concepción	Concepción
	SASONA	Concepción	Coronel
	Pacific Fishers	Concepción	Coronel
	Congelados del Pacífico	Concepción	Talcahuano
	Unifish Canning	Concepción	Talcahuano
	Agromar	Concepción	Talcahuano
Fish flour production	Pesquera del Cabo S.A.	Concepción	Coronel
	Pesquera Conifish	Concepción	Coronel
	Pesquera Del Norte	Concepción	Coronel
	Pesquera Camanchaca	Concepción	Talcahuano
	Pesquera El Golfo	Concepción	Talcahuano
	Pesquera San José	Concepción	Talcahuano
	Pesquera Quurbosa	Concepción	Talcahuano
	Pesquera Itata	Concepción	Talcahuano
	Pesquera Landes	Concepción	Talcahuano
	Pesquera Alimar	Concepción	Talcahuano
	Pesquera Iquique-Guayane	Concepción	Talcahuano
	Pesquera Vásquez	Concepción	Talcahuano

Table IX.1. Overview of the companies associated to the studied industrial activities in the VIII Region, Chile [232].

Industrial activity	Associated companies	Province	Commune
Sugar manufacture	Iansa	Ñuble	Chillán
	Iansa	Bio Bio	Los Angeles
Dye and finished textiles production	Machasa	Concepción	Chiguayante
	Bellavista Oveja Tomé	Concepción	Tomé
	Gacel	Concepción	Concepción
	Albano	Concepción	Concepción
Sawmills	Bosques Arauco	Arauco	Arauco
	Manufacturas Mallines	Arauco	Arauco
	Aserradero Horcones	Arauco	Arauco
	Aserradero Horcones 2	Arauco	Arauco
	Aserradero Colorado	Arauco	Curanilahue
	Andinos	Ñuble	Yungay
	Aserraderos Mininco	Bio Bio	Cabrero
	Aserraderos Arauco	Bio Bio	Cabrero
	Aserradelo La Araucana	Bio Bio	Los Alamos
	Aserraderos Mininco	Bio Bio	Mulchén
	Aserraderos Mininco	Bio Bio	Nacimiento
Fiber Panels production	Paneles Arauco	Arauco	Arauco
	Fibranova	Bio Bio	Cabrero
	Fibramold	Bio Bio	Cabrero
	Industrias Rio Itata	Ñuble	Trehuaco
	Paneles Itata	Ñuble	Quillón
	Masisa	Concepción	Chiguayante
	Masisa	Concepción	San Pedro de la Paz
Pulp, paper and cardboard manufacture	Celulosa Arauco	Arauco	Arauco
	CMPC Celulosa Planta Laja	Bio Bio	Laja
	CMPC Celulosa Planta Santa Fe	Bio Bio	Nacimiento
	Norke Skog	Concepción	San Pedro de la Paz
	Papelera Concepción	Concepción	San Pedro de la Paz
Chemical agents manufacture	Oxiquim	Concepción	Coronel
	Georgia Pacific Resinas Ltda.	Concepción	San Pedro de la Paz
	Occidental Chemical Chile	Concepción	Talcahuano
	Eka Nobel Chile	Concepción	Talcahuano
	AGA	Concepción	Talcahuano
	Petroquímica Dow	Concepción	Hualpén
	Petropower	Concepción	Hualpén
	Petroquim	Concepción	Hualpén

Table IX.1. Overview of the companies associated to the studied industrial activities in the VIII Region, Chile [232].

Industrial activity	Associated companies	Province	Commune
Petroleum refination	Enap Refinerías Bio Bio	Concepción	Hualpén
Cement, yeast and carbonate production	Cementos Bio Bio	Concepción	Talcahuano
	Ready Mix	Concepción	Talcahuano
	Cementos Polpaico	Concepción	Coronel
Glass manufacture	Vidrios Lirquén	Concepción	Lirquén
Manufacture of metallic products	Moly Cop	Concepción	Talcahuano
	Edyce	Concepción	Talcahuano
	Inchalam	Concepción	Talcahuano
	Metalurgica Cerrillos	Concepción	Talcahuano
	Quimet SAC	Concepción	Coronel
Marine shipyards and arsenals	Astilleros Marco Thno. Ltda.	Concepción	Talcahuano
	Maestranza Solesa	Concepción	Talcahuano
	ASMAR	Concepción	Talcahuano
Industrial and household waste management companies	Copiulemu S.A.	Concepción	Florida

Table IX.1. Overview of the companies associated to the studied industrial activities in the VIII Region, Chile [232].

Company	Province	Commune	Location
ESSO	Concepción	Concepción	San Martin esq. Orompello
ESSO	Concepción	Concepción	Avda. Collao
ESSO	Concepción	Concepción	Av Alessandri (Pte. Nuevo)
ESSO	Concepción	Concepción	Los Carrera (esq. Tucapel)
ESSO	Concepción	Concepción	Avda. General Bonilla
ESSO	Concepción	Concepción	Avda. Pedro de Valdivia
ESSO	Concepción	Concepción	Avda. 21 de Mayo
ESSO	Concepción	Concepción	Prat (esq. Los Carrera)
YPF	Concepción	Concepción	Avda. General Bonilla
YPF	Concepción	Concepción	Pedro Lagos
YPF	Concepción	Concepción	Los Carrera (esq Salas)
YPF	Concepción	Concepción	Los Carrerra (esq Lautaro)
YPF	Concepción	Concepción	Janequeo
SHELL	Concepción	Concepción	Los Carrera esq. Licoyán
SHELL	Concepción	Concepción	Paicaví
SHELL	Concepción	Concepción	Paicaví esq. Bulnes
SHELL	Concepción	Concepción	M. Gutierrez
SHELL	Concepción	Concepción	P. de Valdivia
SHELL	Concepción	Concepción	Av. Collao
SHELL	Concepción	Concepción	Collao
SHELL	Concepción	Concepción	Maipú (esq Colo Colo)
COPEC	Concepción	Concepción	Avda. Prat (esq Rozas)
COPEC	Concepción	Concepción	Tegualda (Terminal de Buses)
COPEC	Concepción	Concepción	Los Carrera (esq. Colo Colo)
COPEC	Concepción	Concepción	Avda. Prat (esq Bilbao)
COPEC	Concepción	Concepción	Maipú
COPEC	Concepción	Concepción	Paicaví (esq M Rodriguez)
COPEC	Concepción	Concepción	Camino a Bulnes (Palomares)
COPEC	Concepción	Concepción	21 de Mayo esq Dr. Oliver
COPEC	Concepción	Concepción	Anibal Pinto
COPEC	Concepción	Concepción	Ejercito
COPEC	Concepción	Concepción	Avda. Collao
COPEC	Concepción	Concepción	M Rodríguez
ESSO	Concepción	San Pedro de la Paz	P. Aguirre Cerda
ESSO	Concepción	San Pedro de la Paz	P. Aguirre Cerda
COPEC	Concepción	San Pedro de la Paz	P. Aguirre Cerda
COPEC	Concepción	San Pedro de la Paz	Camino a Coronel
COPEC	Concepción	San Pedro de la Paz	Los Canelos
SHELL	Concepción	San Pedro de la Paz	Michimalongo
SHELL	Concepción	Chiguayante	M. Rodríguez
COPEC	Concepción	Chiguayante	O´Higgins
COPEC	Concepción	Chiguayante	M. Rodríguez
ESSO	Concepción	Tome	Serrano
SHELL	Concepción	Tome	M. Egaña
COPEC	Concepción	Tome	Latorre (esq Brasil)
COPEC	Concepción	Tome	Acceso a Pingueral
ESSO	Concepción	Penco	Camino a Penco
COPEC	Concepción	Penco	Camino a Penco

Table IX.2. Identification of petrol stations in the provinces of Concepción and Arauco, VIII Region, Chile [232].

Company	Province	Commune	Location
COPEC	Concepción	Penco	Calle Penco
COPEC	Concepción	Penco	Camino a Penco
COPEC	Concepción	Penco	Camilo Henriquez (Lirquén)
YPF	Concepción	Penco	Ruta del Itata
SHELL	Concepción	Penco	Yerbas Buenas
ESSO	Concepción	Talcahuano	Malaquías Concha
ESSO	Concepción	Talcahuano	Avda. Colón
ESSO	Concepción	Talcahuano	Avda Las Golondrinas
YPF	Concepción	Talcahuano	Autopista
YPF	Concepción	Talcahuano	Toribio Medina
SHELL	Concepción	Talcahuano	Bilbao
SHELL	Concepción	Talcahuano	Colón esq Desiderio García
SHELL	Concepción	Talcahuano	Las Torcazas
SHELL	Concepción	Talcahuano	Colón (esq Cañete)
SHELL	Concepción	Talcahuano	Av. Las Golondrinas
COPEC	Concepción	Talcahuano	Valdivia (Ventoteca)
COPEC	Concepción	Talcahuano	Pedro Montt (Base Naval)
COPEC	Concepción	Talcahuano	Caleta Tumbes (Base Naval)
COPEC	Concepción	Talcahuano	Gran Bretaña
COPEC	Concepción	Talcahuano	Pérez Gacitua (Morro)
COPEC	Concepción	Talcahuano	Pedro Montt (Pto Sn Vicente)
COPEC	Concepción	Talcahuano	Avda, Colón
COPEC	Concepción	Talcahuano	A Vespucio (autopista)
COPEC	Concepción	Talcahuano	Av. La Concepción
COPEC	Concepción	Talcahuano	Autopista
BLANCO	Concepción	Talcahuano	J. Repullo
ESSO	Concepción	Coronel	Paso Seco (Camilo Olavarria)
ESSO	Concepción	Coronel	M Montt (esq Lautaro)
YPF	Concepción	Coronel	Camino a Coronel
COPEC	Concepción	Coronel	Los Carrera esq Serrano
COPEC	Concepción	Coronel	Camino a Coronel
COPEC	Concepción	Coronel	Sotomayor
SHELL	Concepción	Coronel	Camino a Coronel
YPF	Concepción	Lota	Serrano
SHELL	Concepción	Lota	C. Cousiño (Lota Alto)
SHELL	Concepción	Lota	Valle Colcura, Ruta P 160
COPEC	Concepción	Lota	Bannen esq Serrano
COPEC	Arauco	Arauco	Condell esq Körner
COPEC	Arauco	Arauco	Los Horcones
COPEC	Arauco	Arauco	Los Horcones
SHELL	Arauco	Arauco	Ruta P 160
SHELL	Arauco	Curanilahue	Avda O´Higgins
COPEC	Arauco	Curanilahue	Raval
COPEC	Arauco	Curanilahue	Avda O´Higgins
COPEC	Arauco	Lebu	Andrés Bello
COPEC	Arauco	Lebu	Puerto Fluvial
COPEC	Arauco	Lebu	Rivera Norte Río Lebu
COPEC	Arauco	Los Alamos	Ignacio Carrerra Pinto

Table IX.2. Identification of petrol stations in the provinces of Concepción and Arauco, VIII Region, Chile [232].

Company	Province	Commune	Location
COPEC	Arauco	Los Alamos	Avda Diego Portales
COPEC	Arauco	Contulmo	Ignacio Carrera Pinto
ESSO	Arauco	Cañete	Avda. Presidente Frei
SHELL	Arauco	Cañete	Saavedra
SHELL	Arauco	Cañete	Avda, Presidente Frei
COPEC	Arauco	Cañete	Avda. Presidente Frei
YPF	Arauco	Tirua	Lote A
COPEC	Arauco	Tirua	Camino a Tirua

Table IX.3. Identification of mining environmental liabilities in the provinces of Concepción and Arauco, VIII Region, Chile [232]..

Type of mining passive o	Province	Commune	Location
Coal mining passive	Concepción	Coronel	Fundo Yobilo
Coal mining passive	Concepción	Coronel	La Colonia
Coal mining passive	Concepción	Coronel	Cerro Obligado
Coal mining passive	Concepción	Coronel	Merquín
Coal mining passive	Concepción	Coronel	La Virgen
Inerts dumping place	Concepción	Lota	Pique Carlos Cousiño
Coal mining passive	Concepción	Lota	Población Caleros Sur

Table IX.4. Identification of environmental liabilities in the provinces of Concepción and Arauco, VIII Region, Chile.

Type of environmental passive	Province	Commune	Location
Sawdust deposit	Arauco	Los Alamos	Antihuala
Sawdust deposit	Arauco	Los Alamos	Tres Pinos
Sawdust deposit	Arauco	Cañete	Huillinco
Sawdust deposit	Concepción	Tomé	Punta de Parra

Table IX.5. Identification of illegal dumping sites in the provinces of Concepción and Arauco, VIII Region, Chile.

Landfill	Province	Commune	Location
Sector Camino a Ranquilmo	Arauco	Los Alamos	7 km al SO de Los Alamos
Lebu	Arauco	Lebu	3 km al O de Lebu
Sector Camino a Cayucupil	Arauco	Cañete	5 km al E de Cañete
Servimar	Concepción	Coronel	1,5 km al S de Coronel
Frutillares	Concepción	Tomé	3 km al N de Tomé
Cosmito	Concepción	Penco	6 km al S de Penco
Carriel Norte	Concepción	Talcahuano	3 km al S de Talcahuano

Annex X: Risk assessment of suspected sites in the Bio-Bio Region, Chile

Form VII.1. Form for the first evaluation of sites identified as potentially contaminated

Serie de identificación:

1. Información general del sitio

Nombre sitio:
Nombre de institución responsable:
Tamaño: m²

Provincia:
Comuna:
Georeferencias:

2. Clasificación de acuerdo a principales rubros en estudio

☐ Actividades Industriales.
☐ Botaderos Clandestinos y Vertederos.
☐ Actividades Mineras (Pasivos mineros).
☐ Estaciones de Servicio y zonas de almacenamiento de hidrocarburos.
☐ Pasivos Ambientales (receptores de contaminación).

3. Tipo de actividad desarrollada

Caso 1: Actividades Industriales

Tipo de Actividad Industrial: ------ Seleccione una actividad industrial ------
Formas de Contaminación: ☐ Efluentes
☐ Derrames
☐ Infiltraciones
☐ Emisiones
☐ Disposición de residuos sólidos
☐ Otras

Caso 2: Botaderos Clandestinos y Vertederos

Tipo de relleno sanitario: ------ Seleccione un tipo de relleno ------
Tipo de Residuos: ☐ Metales
☐ Orgánicos
☐ Plaguicidas
☐ Mezclas complejas
☐ Otro

Caso 3: Actividades Mineras
Tipo de Actividad Minera: ------ Seleccione una actividad minera ------

Caso 5: Pasivos ambientales
Tipo de Pasivo Ambiental:

4. Estratos ambientales impactados

☐ Suelo
☐ Aire
☐ Agua superficial
☐ Lago ☐ Río ☐ Laguna ☐ Canal
☐ Agua subterránea
☐ Otro:

5. Evaluación del factor de dispersión de contaminación a través de aguas subterráneas

Seleccione el o los casos más adecuados de la siguiente tabla.

☐ No utilisation possibilities for groundwater
☐ Within influence area of water well
☐ Run-off water, pore groundwater sufficient only for individual and/or local water supplies.
☐ Inside a (potential) area of regional and/or national drinking water supply
☐ All declared sanctuaries and protected areas (phase III), groundwater body with national importance
☐ All declared sanctuaries and protected areas (phase I + II)
☐ In area of influence of an actual drinking water supply

6. Evaluación del factor de dispersión de contaminación a través de agues superficiales

Seleccione el o los casos más adecuados de la siguiente tabla.

☐ No surface-water within 25 m surrounding and surface-water with possibility of contact to humans no more than after huge thinning of a potential emission and surface water without any special utilisation claim.
☐ Surface water within directly urban areas or leisure areas (or in nature reserve), larger thinning possible.
☐ Surface water within directly urban areas or leisure areas (or in nature reserve), no larger thinning probable resp. utilisation for in-shore filtration recovery or ground water-accumulation

7. Evaluación del factor de dispersión de contaminación a través de agues superficiales

Seleccione el o los casos más adecuados de la siguiente tabla.

☐ No possible use of surface.
☐ Agricultural utilisation of surface possible.
☐ Agricultural utilisation of surface or situation within natural reserve.
☐ In urban areas without possibility of direct contact to children.
☐ Usage of area and/or usage of direct surrounding as leisure area (also children‘s playground).

	Rodrigo Agüero Pérez
Fecha	Responsable de esta ficha

Table X.1. Summary of calculations for industrial sites [a]

Serial Nr.	Act. Type	S-Value	Probability	f(Probability)	Extension	f(Extension)	f(G)	f(S)	f(N)	f(G,S,N)	R
VIII-01	23	5	3	1,1	L	1,2	1,5	1	1,3	1,08	7,1
VIII-02	11	5	1	0,9	S	1	1,3	1,7	1,3	1,13	5,1
VIII-03	11	5	1	0,9	S	1	1	1,7	1	1,07	4,8
VIII-04	11	5	1	0,9	S	1	1	1,7	1	1,07	4,8
VIII-05	11	5	1	0,9	S	1	1	1,7	1	1,07	4,8
VIII-06	11	5	1	0,9	M	1,1	1	1,7	1,3	1,1	5,4
VIII-07	11	5	1	0,9	M	1,1	1	1	1	1	5,0
VIII-08	11	5	1	0,9	M	1,1	1	1	1	1	5,0
VIII-10	11	5	1	0,9	S	1	1	1,7	1	1,07	4,8
VIII-11	11	5	1	0,9	S	1	1	1,7	1	1,07	4,8
VIII-12	11	5	1	0,9	M	1,1	1	1	1,3	1,03	5,1
VIII-13	11	5	1	0,9	S	1	1	1,7	1	1,07	4,8
VIII-14	11	5	1	0,9	S	1	1	1,7	1	1,07	4,8
VIII-15	11	5	1	0,9	S	1	1	1,7	1	1,07	4,8
VIII-16	35	5	1	0,9	M	1,1	1	1,7	1	1,07	5,3
VIII-17	35	5	1	0,9	M	1,1	1,3	1,7	1,3	1,13	5,6
VIII-18	35	5	1	0,9	S	1	1	1,7	1,3	1,1	5,0
VIII-19	35	5	1	0,9	S	1	1	1,7	1	1,07	4,8
VIII-20	35	5	1	0,9	S	1	1	1,7	1	1,07	4,8
VIII-21	37	5	3	1,1	M	1,1	1,5	1,2	1,3	1,1	6,7
VIII-22	37	5	3	1,1	M	1,1	1,5	1,2	1,3	1,1	6,7
VIII-23	37	5	3	1,1	M	1,1	1,5	1,2	1,3	1,1	6,7
VIII-23	37	5	3	1,1	M	1,1	1,5	1,2	1,3	1,1	6,7
VIII-25	37	5	3	1,1	S	1	1	1,7	1,3	1,1	6,1
VIII-26	37	5	3	1,1	S	1	1	1,7	1,3	1,1	6,1
VIII-27	37	5	3	1,1	M	1,1	1,3	1,7	1,3	1,13	6,8
VIII-28	37	5	3	1,1	M	1,1	1	1,7	1,3	1,1	6,7
VIII-29	37	5	3	1,1	M	1,1	1,5	1,7	1,3	1,15	7,0

[a)] Sites highlighted in yellow have been classified as Priority 1 according to the first risk assessment procedure.

Table X.1. Summary of calculations for industrial sites

Serial Nr.	Act. Type	S-Value	Probability	f(Probability)	Extension	f(Extension)	f(G)	f(S)	f(N)	f(G,S,N)	R
VIII-30	37	5	3	1,1	M	1,1	1,5	2	1,3	1,18	7,1
VIII-31	37	5	3	1,1	S	1	1,3	1,2	1,3	1,08	5,9
VIII-32	37	5	3	1,1	S	1	1,3	1,2	1,3	1,08	5,9
VIII-33	37	5	3	1,1	S	1	1,3	1	1,3	1,06	5,8
VIII-34	37	5	3	1,1	S	1	1,3	1,7	1,3	1,13	6,2
VIII-35	37	5	3	1,1	L	1,2	1,7	1,7	1,7	1,21	8,0
VIII-36	37	5	3	1,1	L	1,2	1,5	1,7	1,7	1,19	7,9
VIII-37	37	5	3	1,1	M	1,1	1	1	1,3	1,03	6,2
VIII-38	37	5	3	1,1	M	1,1	1	1	1,3	1,03	6,2
VIII-39	37	5	3	1,1	S	1	1,3	1,7	1,3	1,13	6,2
VIII-40	6	5	2	1	L	1,2	1,5	1,7	2	1,22	7,3
VIII-41	37	5	3	1,1	L	1,2	1,3	1,7	1,7	1,17	7,7
VIII-42	6	5	2	1	L	1,2	1,5	1,7	1,3	1,15	6,9
VIII-43	6	5	2	1	L	1,2	1,5	1	1,7	1,12	6,7
VIII-44	6	5	2	1	L	1,2	1,5	1,2	1,3	1,1	6,6
VIII-45	6	5	2	1	M	1,1	1,5	1,2	1,3	1,1	6,1
VIII-46	6	5	2	1	M	1,1	1	1	1	1	5,5
VIII-47	6	5	2	1	M	1,1	1,8	1,2	1,7	1,17	6,4
VIII-48	6	5	2	1	L	1,2	1,8	1	1,3	1,11	6,7
VIII-49	6	5	2	1	L	1,2	1,3	1	1	1,03	6,2
VIII-50	6	5	2	1	L	1,2	1,8	2	2	1,28	7,7
VIII-51	26	5	1	0,9	L	1,2	1,5	1,7	1,7	1,19	6,4
VIII-52	26	5	1	0,9	S	1	1	2	1	1,1	5,0
VIII-53	26	5	1	0,9	L	1,2	1,5	1,7	1,3	1,15	6,2
VIII-54	6	5	2	1	L	1,2	1	1,7	1,7	1,14	6,8
VIII-55	21	4	3	1,1	S	1	1	1,7	1	1,07	4,7
VIII-56	17	5	3	1,1	M	1,1	1	1,7	1	1,07	6,5
VIII-57	17	5	3	1,1	M	1,1	1,3	1,7	1,3	1,13	6,8
VIII-58	21	4	3	1,1	M	1,1	1,3	1,7	1,3	1,13	5,5
VIII-59	21	4	3	1,1	M	1,1	1	1	1	1	4,8
VIII-60	21	4	3	1,1	M	1,1	1	1,7	1	1,07	5,2

Table X.1. Summary of calculations for industrial sites

Serial Nr.	Act. Type	S-Value	Probability	f(Probability)	Extension	f(Extension)	f(G)	f(S)	f(N)	f(G,S,N)	R
VIII-61	21	4	3	1,1	S	1	1	1,7	1	1,07	4,7
VIII-62	21	4	3	1,1	L	1,2	1	1	1	1	5,3
VIII-63	11	5	1	0,9	S	1	1	1,7	1	1,07	4,8
VIII-64	11	5	1	0,9	S	1	1	1,7	1	1,07	4,8
VIII-65	37	5	3	1,1	L	1,2	1,7	1,5	2	1,22	8,1
VIII-66	37	5	3	1,1	L	1,2	1,7	1,5	1,3	1,15	7,6
VIII-66	37	5	3	1,1	S	1	1,3	1,2	2	1,15	6,3
VIII-68	37	5	3	1,1	M	1,1	1,5	1,5	1,7	1,17	7,1
VIII-69	37	5	3	1,1	M	1,1	1,5	1,5	1,7	1,17	7,1
VIII-70	37	5	3	1,1	S	1	1,3	1,2	1,3	1,08	5,9
VIII-71	37	5	3	1,1	M	1,1	1,3	1,5	1,3	1,11	6,7
VIII-72	37	5	3	1,1	M	1,1	1,3	1,5	1,3	1,11	6,7
VIII-73	37	5	3	1,1	L	1,2	1,5	1,5	2	1,2	7,9
VIII-74	37	5	3	1,1	S	1	1,3	1,2	1,3	1,08	5,9
VIII-75	37	5	3	1,1	M	1,1	1,3	1,5	1,7	1,15	7,0
VIII-76	37	5	3	1,1	M	1,1	1	1,2	1,7	1,09	6,6
VIII-77	37	5	3	1,1	M	1,1	1,5	1,2	1,7	1,14	6,9
VIII-78	37	5	3	1,1	M	1,1	1,3	1,2	1,3	1,08	6,5
VIII-79	37	5	3	1,1	M	1,1	1,3	1	1,7	1,1	6,7
VIII-80	37	5	3	1,1	S	1	1	1	1	1	5,5
VIII-81	37	5	3	1,1	S	1	1	1,2	1	1,02	5,6
VIII-82	37	5	3	1,1	S	1	1,3	1,2	1	1,05	5,8
VIII-83	37	5	3	1,1	M	1,1	1,3	1,2	1,7	1,12	6,8
VIII-84	37	5	3	1,1	S	1	1	1,7	1	1,07	5,9
VIII-85	37	5	3	1,1	L	1,2	1,5	1,5	1,7	1,17	7,7
VIII-86	37	5	3	1,1	S	1	1,3	1,5	1	1,08	5,9
VIII-87	37	5	3	1,1	S	1	1,3	1,5	1	1,08	5,9
VIII-88	37	5	3	1,1	S	1	1,3	1,2	1,3	1,08	5,9
VIII-89	37	5	3	1,1	S	1	1,3	1,2	1,3	1,08	5,9

Table X.1. Summary of calculations for industrial sites

Serial Nr.	Act. Type	S-Value	Probability	f(Probability)	Extension	f(Extension)	f(G)	f(S)	f(N)	f(G,S,N)	R
VIII-90	37	5	3	1,1	S	1	1	1,7	1,3	1,1	6,1
VIII-91	37	5	3	1,1	M	1,1	1,5	1,5	1,3	1,13	6,8
VIII-92	37	5	3	1,1	M	1,1	1	1,7	1	1,07	6,5
VIII-93	37	5	3	1,1	S	1	1	2	1	1,1	6,1
VIII-93	37	5	3	1,1	S	1	1	1,7	1	1,07	5,9
VIII-95	37	5	3	1,1	S	1	1	1	1	1	5,5
VIII-96	37	5	3	1,1	L	1,2	1,3	1,2	1,3	1,08	7,1
VIII-97	37	5	3	1,1	S	1	1,3	1,5	1	1,08	5,9

Table X.2. Summary of calculations for landfills

Serial Nr.	Act. Type	S-Value	Probability	f(Probability)	Extension	f(Extension)	f(G)	f(S)	f(N)	f(G,S,N)	R
VIII-98	8	7	3	1,1	M	1	1,3	1,5	1,3	1,11	8,547
VIII-99	8	5,5	3	1,1	M	1	1,3	1,5	1,3	1,11	6,7155
VIII-100	8	4	3	1,1	M	1	1,3	1,2	1,3	1,08	4,752
VIII-101	8	8	3	1,1	M	1	1	1,7	1,3	1,1	9,68
VIII-102	8	5	3	1,1	M	1	1	1,2	1,3	1,05	5,775
VIII-103	8	5,5	3	1,1	M	1	1,3	1,2	1,3	1,08	6,534
VIII-104	8	9	3	1,1	L	1,1	1,3	1,7	1,7	1,17	10

Table X.3. Summary of calculations for mining environmental liabilities

Serial Nr.	Act. Type	S-Value	Probability	f(Probability)	Extension	f(Extension)	f(G)	f(S)	f(N)	f(G,S,N)	R
VIII-110	34	6	3	1,1	M	1,1	1	2	2	1,2	8,7
VIII-111	34	7	3	1,1	S	0,9	1	2	1,7	1,17	8,1
VIII-112	34	6	3	1,1	S	1	1,3	1,7	1,7	1,17	7,7

Table X.4. Summary of calculations for environmental liabilities

Serial Nr.	Act. Type	S-Value	Probability	f(Probability)	Extension	f(Extension)	f(G)	f(S)	f(N)	f(G,S,N)	R
VIII-105	37	5	3	1,1	M	1,1	1,3	1,2	1,3	1,08	6,534
VIII-106	37	5	3	1,1	M	1,1	1	1,2	1	1,02	6,171
VIII-107	37	5	3	1,1	M	1,1	1	1,2	1	1,02	6,171
VIII-108	37	6	3	1,1	M	1,1	1,5	1,5	2	1,2	8,712
VIII-109	37	5	3	1,1	M	1,1	1,5	1,7	1	1,12	6,776
VIII-115	6	6	3	1,1	S	1	1,8	1,5	1,3	1,16	7,656
VIII-116	5	6	3	1,1	S	1	2	1,5	1,7	1,22	8,052

Annex XI: Land register of suspected sites in the Bio-Bio Region: Graphical representation of the problem dimension

Figure XI.1. Aserradero Carampangue, Arauco.

Figure XI.2. Aserradero Carampangue, Arauco.

Figure XI.3. Aserradero Carampangue, Arauco.

Figure XI.4. Aserradero Carampangue, Arauco.

Figure XI.5. Aserradero Carampangue, Arauco.

Figure XI.6. Aserradero Carampangue, Arauco.

Figure XI.7. Paneles Arauco, Arauco.

Figure XI.8. Paneles Arauco, Arauco.

Figure XI.9. Aserradero Maderera Industrial El Colorado, Curanilahue.

Figure XI.10. Aserradero Maderera Industrial El Colorado, Curanilahue.

Figure XI.11. Aserradero Maderera Industrial El Colorado, Curanilahue.

Figure XI.12. Aserradero Maderera Industrial El Colorado, Curanilahue.

Figure XI.13. Aserradero Maderera Industrial El Colorado, Curanilahue.

Figure XI.14. Aserradero Maderera Industrial El Colorado, Curanilahue.

Figure XI.15. Aserradero Maderera Industrial El Colorado, Curanilahue.

Figure XI.16. Central Bocamina, Coronel.

Figure XI.17. Central Bocamina, Coronel.

Figure XI.18. Central Bocamina, Coronel.

Figure XI.19. Central Bocamina, Coronel.

Annex XII: Selected publications

Journals

Bezama, A., Navia, R., Novak, J. & Lorber K. E. (2004): Novel approaches for the management and redevelopment of contaminated sites. *Österreichische Abfall- und Wasserwirtschaft* 56, 11-12, 139 – 144.

Pavlov, P., Bezama, A. & Navia, R. (2004): Improvement of clay impermeability by using cement as an additive. *Berg- und Hüttenmännische Monatshefte* 149(6), 223-224.

Bezama, A., Agüero, R., Barrera, S., Márquez, F. & Lorber, K.E. (2006): Land register and evaluation of contaminated sites in an industrial Chilean Region: Identification and evaluation of suspected sites. Submitted to: *Waste Management*.

In preparation:

Bezama, A., Novak, J., Erhart-Schippek, W. & Lorber, K.E.: Benchmarking of management technologies for contaminated sites. To be submitted to: *Waste Management and Research.*

Bezama, A., Agüero, R., Barrera, S., Márquez, F. & Lorber, K.E.: Development of a preliminary procedure for the identification and evaluation of contaminated sites in developing countries. To be submitted to: *Waste Management.*

Bezama, A., Szarka, N., Wolfbauer, J. & Lorber, K.E.: The use of the Balanced Scorecard for decision-making in contaminated sites management. To be submitted to: *Water, Air and Soil Pollution.*

Bezama, A., Szarka, N., Wolfbauer, J. & Lorber, K.E.: Development of a knowledge-based model for contaminated sites management based on the European experience and its application to developing countries. To be submitted to: *Environmental Science and Technology.*

Bezama, A., & Lorber, K.E.: Lessons learned for a more efficient know-how transfer to South American countries in the fields of solid waste and contaminated sites management. To be submitted to: *Waste Management and Research.*

Congress proceedings

Bezama, A., Lorber, K.E., Novak, J. & Navia, R. (2003): First Steps in the Development of an Expert System for Brownfields Management Based on the Austrian Experience. VI National Polish Scientific Conference on Complex and Detailed Problems of Environmental Engineering. Politechnika Koszalinska. Koszalin, Poland.

Bezama, A., Lorber, K. E., Navia, R. & Novak, J. (2003): An Expert System for the selection of an optimised alternative for the management of PAH/CHC contaminated sites: definitions and future expectations. Ninth International Waste Management and Landfill Symposium – Sardinia 2003, Sta. Margherita di Pula, Italy.

Bezama, A., Navia, R., Novak, J. & Lorber, K.E. (2003): Environmentally Sound Approaches for the Remediation of Industrial Contaminated Sites. Brownfields 2003: Growing a greener America. October 27-29, Portland (OR), U.S.A.

Bezama, A., Navia, R., Novak, J. & Lorber, K.E. (2003): Development of Decision Support Tools for brownfields and contaminated sites management and redevelopment. Brownfields 2003: Growing a greener America. October 27-29, Portland (OR), U.S.A.

Lorber, K.E., Bezama, A., Novak, J. & Erhart-Schippek, W. (2004): Management and Redevelopment of Old Landfill Sites: Case Study Köglerweg, Austria. Enviro 04 Convention & Exhibition. 28 March – 1 April, Sydney, Australia.

Bezama, A., Novak, J. & Lorber, K.E. (2004): An Expert System For The Management Of Industrial Contaminated Sites. Enviro 04 Convention & Exhibition. 28 March – 1 April, Sydney, Australia.

Novak, J., Bezama, A. & Lorber, K.E. (2004): Decision Support System for Brownfield's Redevelopment. Enviro 04 Convention & Exhibition. 28 March – 1 April, Sydney, Australia.

Navia, R., Bezama, A., Lorber, K.E., Valenzuela, R. & Reyes, C. (2004): Contaminated soil as an alternative raw material in Chilean cement production facilities. Depotech 2004, Nov. 24-26, Leoben, Austria.

Navia, R., Fuentes, B., Bezama, A., Lorber, K.E. & Diez, M. C. (2004): The use of volcanic soil as a sanitary landfill liner and its capacity to retain some specific heavy metals. *ISWA World Environment Congress and Exhibition*, Oct. 17-21, Rome, Italy.

Lorber, K.E., Bezama, A., Novak, J. & Navia, R. (2004): A Novel Approach for the Redevelopment of Old Landfill Sites. *ISWA World Environment Congress and Exhibition*, Oct. 17-21, Rome, Italy.

Bezama, A., Szarka, N., Navia, R. & Lorber, K.E. (2005): Metodología de selección de alternativas tecnológicas para el manejo de sitios contaminados. *XI Congreso Chileno de Ingeniería Química*. Nov. 1-4, Pucón, Chile.

Bezama, A. (2005): Experiences on transferring technological know-how to South American countries in the fields of solid waste and contaminated sites management. Proceedings of the International Conference on "The role of the Appropriate technologies in Cooperation Projects". Dec. 16. Desenzano del Garda, Italy.