COMMITTEE ON
THE CHALLENGES OF
MODERN SOCIETY

EPA 542-R-01-002
January 2001
www.clu-in.org
www.nato.int/ccms

# NATO/CCMS Pilot Study

## Evaluation of Demonstrated and Emerging Technologies for the Treatment of Contaminated Land and Groundwater (Phase III)

**2000**
**SPECIAL SESSION**

**Decision Support Tools**

Number 245

NORTH ATLANTIC TREATY ORGANIZATION

# NATO/CCMS Pilot Study

# Evaluation of Demonstrated and Emerging Technologies for the Treatment and Clean Up of Contaminated Land and Groundwater (Phase III)

## SPECIAL SESSION ON

## Decision Support Tools

**Wiesbaden**
**June 26-30, 2000**

**January 2001**

**NOTICE**

This report was prepared under the auspices of the North Atlantic Treaty Organization's Committee on the Challenges of Modern Society (NATO/CCMS) as a service to the technical community by the United States Environmental Protection Agency (U.S. EPA). The report was funded by U.S. EPA's Technology Innovation Office. The report was produced by Environmental Management Support, Inc., of Silver Spring, Maryland, under U.S. EPA contract 68-W-00-084. Mention of trade names or specific applications does not imply endorsement or acceptance by U.S. EPA.

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# INTRODUCTION

The Council of the North Atlantic Treaty Organization (NATO) established the Committee on the Challenges of Modern Society (CCMS) in 1969. CCMS was charged with developing meaningful programs to share information among countries on environmental and societal issues that complement other international endeavors and to provide leadership in solving specific problems of the human environment. A fundamental precept of CCMS involves the transfer of technological and scientific solutions among nations with similar environmental challenges.

The management of contaminated land and groundwater is a universal problem among industrialized countries, requiring the use of existing, emerging, innovative, and cost-effective technologies. This document summarizes the special session on decision support systems from the third meeting of the Phase III Pilot Study on the Evaluation of Demonstrated and Emerging Technologies for the Treatment and Clean Up of Contaminated Land and Groundwater. The United States is the lead country for the Pilot Study, and Germany and The Netherlands are the Co-Pilot countries. The first phase of the pilot study was successfully concluded in 1991, and the results were published in three volumes. The second phase, which expanded to include newly emerging technologies, was concluded in 1997. Final reports documenting 52 completed projects and the participation of 14 countries were published in June 1998. Through this pilot study, critical technical information is made available to participating countries and the world community.

The Phase III study focuses on the technical approaches for treating contaminated land and groundwater. This includes issues of sustainability, environmental merit, and cost-effectiveness, in addition to continued emphasis on emerging remediation technologies. The objectives of the study are to critically evaluate technologies, promote the appropriate use of technologies, use information technology systems to disseminate the products, and to foster innovative thinking in the area of contaminated land.

The first meeting of the Phase III study was held in Vienna, Austria, on February 23-27, 1998. The meeting included a special technical session on treatment walls and permeable reactive barriers. The proceedings of the meeting and of the special technical session were published in May 1998. The second meeting of the Phase III Pilot Study convened in Angers, France, on May 9-14, 1999, with representatives of 18 countries attending. A special technical session on monitored natural attenuation was held. This report and the general proceedings of the 1999 annual meeting were published in October 1999. This third meeting was held in Wiesbaden, Germany from June 26-30, 2000. The special technical focused on decision support tools.

This publication is the report from the special session on decision support tools. This session was chaired by Dr. Paul Bardos from r3 environmental technology Ltd (UK) and Dr. Terry Sullivan from Brookhaven National Laboratory (US).

This and many of the Pilot Study reports are available online at http://www.nato.int/ccms/. General information on the NATO/CCMS Pilot Study may be obtained from the country representatives listed at the end of the report. Further information on the presentations in this decision support tools report should be obtained from the individual authors.

Stephen C. James
Walter W. Kovalick, Jr., Ph.D.
Co-Directors

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## EXECUTIVE SUMMARY

Environmental management of contaminated lands is a complex process requiring a wide variety of decisions encompassing different technical, social, and political questions. Decision support for contaminated land management is an emerging field. Decision support involves integration of expertise and data, followed by analysis and interpretation of the results to produce outcomes in terms of decision variables (health risk, cost, suitability, etc.). The decision support can be in the form of guidance that provides a framework for performing the analysis or software that has codified the expertise to allow more rapid analysis by many. The magnitude and similarity between contaminated land management problems has led to development of several decision support tools (DSTs) to address different aspects of the problem (site characterization, cost-benefit, risks, sustainable development, etc.).

Four major categories of DST use were identified during the special session discussions:

- Written guidance produced, for example, by regulatory bodies,
- Identifying sites on a regional or organizational (e.g., corporate) basis and setting management/ policy goals,
- Prioritization among different sites within a single area of responsibility,
- Using DST for specific tasks at a single site. Examples of these approaches include analysis of human health risks, remedy selection, site characterization, and cost-benefit analysis. In most applications, a single decision criterion is evaluated. However, use of multi-criteria analysis (MCA) and life cycle analysis (LCA) approaches are often found.

The session had a series of invited talks on different aspects of decision support including implementation of decision support tools. This report contains the following papers:

- Framework for decision support used in contaminated land management in Europe and North America
- Geospatial decision frameworks for remedial design and secondary sampling
- Decision support tools: applications in remediation technology evaluation and selection
- Common factors in decision-making and their implications for decision support for contaminated land in a multi-objective setting
- Case Study - Cost benefit analysis/multi-criteria analyses for a remediation project
- Modelling of financial risks of remediation
- Decision support using Life Cycle Assessment in Soil Remediation Planning
- Approaches to decsion support in the context of sustainable development
- Managing environmental data

In addition, two guided discussion sessions were conducted and one set of written questions was prepared and distributed to the conference participants. Responses from the questions were analyzed and the results were reported at the meeting. The discussion sections focused on obtaining information on the uses of decision support tools and the strengths and limitations of these tools. The questionnaire focused on gathering information on the use of decision support in the different countries participating in the meeting. These discussions have been summarized in the closing paper of this report: *Review of discussions about decision support issues in Europe and North America at The NATO/CCMS Special Session, and overall conclusions.* The main findings of this discussion are as follows.

The major advantage of using *appropriate* DST's is that they can ensure the decision making process is robust, consistent, transparent and reproducible. Specific advantages include:

- Providing a means of relatively easy analysis for multiple scenarios,
- Optimizing the contaminated land management process (leading to lower costs),

- Incorporating uncertainties into the decision framework to enhance the decision making process. (This permits the decision to be based on the problem holder's aversion to failure).
- Improving communication between various stakeholder groups.
- Use as an educational tool.
- Improving the transparency of the process through documenting all parameters and assumptions used in the analysis and explaining the approach used to reach a decision.

However, current DSTs do suffer some limitations, which affect their usefulness.

- Gaining acceptability of a DST with all stakeholders can be difficult.
- Verification/validation of DST performance can be technically challenging
- If the assumptions and data used by DST are not understood, output from the DST may be viewed as "black box" information and may not be trusted. Proper use of DSTs requires users and interested stakeholders receive training on the theory, application and limitations of the DST. Decision support tools must be maintained to keep current, relevant and useful.
- *Garbage In – Garbage Out*: a decision support tool is only as good as the data and assumptions used to perform the analysis

# OPENING COMMENTS TO THE SPECIAL SESSION ON DECISION SUPPORT TOOLS

Paul Bardos[1] and Terry Sullivan[2]

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## BACKGROUND

The Council of North Atlantic Treaty Organisation (NATO) established the Committee on the Challenges of Modern Society (CCMS) in 1969. The CCMS was charged with developing meaningful environmental and social programmes that complement other international initiatives in solving specific problems of the human environment. A major activity of the CCMS is the transfer of technological and scientific solutions and experiences among nations with similar environmental challenges. Further information about the work of the CCMS is available on *www.nato.int/ccms/info.htm*.

In 1997 the NATO CCMS adopted a proposal from the USA for a Pilot Study on treatment technologies. It will run from 1998 to 2002, with a final report in 2003 and is under the direction of the USA, the Netherlands and Germany.

The NATO/CCMS Pilot Study on the "Evaluation of Demonstrated and Emerging Technologies for the Treatment of Contaminated Land and Groundwater (Phase 3) is the third in a series of Pilot Studies considering remedial technologies. These Pilot Studies followed a Pilot Study on the problems of contaminated land directed by the UK and Germany.

The three NATO/CCMS Pilot Studies on remediation technologies has been perhaps the foremost international forum for the exchange of practical and research experience of remedial technologies. The series includes:

- Phase 1, 1986 to 1991 (Martin *et al.,* 1997; NATO, 1993; Smith *et al* 1998, US EPA, 1995 & 1998)
- Phase 2, 1992 to 1997 (Franzius *et al.*, 1996, US EPA, 1998a)
- Phase 3, 1998 to 2003 (U.S. EPA, 1998b ,1998c, 1999a, 1999b, 2000).

The Phase 3 Pilot Study has attracted participation from the following countries across the world. Australia, Austria, Belgium, Canada, the Czech Republic, Denmark, France, Germany, Greece, Hong Kong, Hungary, Italy, Japan, the Netherlands, New Zealand, Norway, Poland, Portugal, Romania, the Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, the United Kingdom, and the United States have all been represented at one or more meetings by a project, government representative, CCMS Fellow, or an individual expert.

The current Pilot Study continues the theme of emerging research and technology demonstration. At each meeting a special one-day session on a topic of particular interest for the remediation of land contamination is held. In 1998 the special session was on treatment walls (US EPA1998c), and in 1999 it was on monitored natural attenuation (US EPA 1999b).

In 2000 the topic for the special session was decision support issues. This report presents the papers of that special session, and a summary paper of the session discussions and conclusions. It has been published by NATO and the U.S. Environmental Protection Agency as part of an ongoing series of Pilot Study publications. Other publications in this series are listed in the reference section.

## GOALS

The aims of the report on the special session on decision support are to:

1. Provide a general understanding of Decision Support (DS) approaches used in contaminated land remediation / risk management, their use, their features and their strengths and weaknesses, for all the NATO delegates whatever their level of knowledge about DS (a wide range of knowledge has been assumed from poor to expert)

2. Involve the Pilot Study in discussion and to document from this debate:

- perceived needs for and uses of DS from the perspective of end-users
- factors seen are most important in decision making
- evaluation of the strengths and weaknesses of existing DS and their use
- needs for DS development, in particular to take advantages of the opportunities for international collaboration offered by the Pilot Study

3. Inform both the users and potential users of DS, and also DS developers of the state of the art.

## APPROACH

The emphasis of the session was on the use of decision support tools for actual remediation decisions. It considered two perspectives:

- site-specific decision making for example choosing a particular remediation system;
- remediation in terms of a risk management / risk reduction process as part of a wider process of site management.

These were addressed both as general topics and as case studies. Case studies were included to provide information on decision support techniques for specific contamination problems such as remedy selection. In the case studies, the authors present the general process to provide decision support and then discuss the application to a specific problem. The intent of this approach is to provide the interested reader with enough knowledge to determine if the process could be used on their specific set of problems. The general topics included broader issues that are not directly tied to a specific problem. The general topics included papers on the role of stakeholders in the decision process and decision support approaches for sustainable development.

Decision factors were explored from an end-user perspective, rather than what a DS developer would like them to be. Ultimately, it is the end-user that drives the decision process. There are a range of possible end-users, including regulators, property developers, local authorities, and specialist users. Furthermore, national perspectives on the use of DS appear to vary. Eliciting the differences in national perspectives was obtained through discussion and a set of questions provided to all meeting participants. The session sought to display the state-of-the-art in decision support for contaminated land management and define future directions in this area. Important issues pertaining to DS include:

- Are DS tools perceived as being useful?
- How are DS being used?
- What are the advantages and disadvantages to using Decision Support Tools (DST)?
- Are information needs for evaluating contaminated land management options understood?

It is salient to note that DS are a topic for the next call for bids for the EU Framework 5 Programme. The US EPA "owns" a number of detailed data-sets for testing and validation of DS that may offer an opportunity for collaboration. There could well be other R&D synergies too.

## THE SESSION REPORT

While the selected set of papers is not inclusive of all work being done on decision support, it is representative of the state-of-the-art approaches to decision support and covers the spectrum of approaches. The first presentation sets the framework for decision support and defines key terms and common approaches. The topics covered include data management, site characterisation and sample optimisation, life-cycle assessment, multi-criteria analysis, evaluating financial risks to land developers, sustainable development, and stakeholder involvement in the decision process. A range of discussion activities took place to permit audience participation to define issues in decision support. The other papers in this session report are as follows.

- Framework for decision support used in contaminated land management in Europe and North America

- Geospatial decision frameworks for remedial design and secondary sampling

- Decision support tools: applications in remediation technology evaluation and selection

- Common factors in decision-making and their implications for decision support for contaminated land in a multi-objective setting

- Case Study - Cost benefit analysis/multi-criteria analyses for a remediation project

- Modelling of financial risks of remediation

- Decision support using Life Cycle Assessment in Soil Remediation Planning

- Approaches to decsion support in the context of sustainable development

- Managing environmental data

- Review of discussions about decision support issues in Europe and North America at The NATO/CCMS Special Session, and overall conclusions

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Note: Phase 2 and Phase 3 Pilot Study reports are available on *http://www.clu-in.com* and from *http://www.nato.int/ccms*. They are also available from the National Center for Environmental Publications and Information in the USA (fax +1 513 489 8695).

# FRAMEWORK FOR DECISION SUPPORT USED IN CONTAMINATED LAND MANAGEMENT IN EUROPE AND NORTH AMERICA

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## SUMMARY

Effective contaminated land management requires a number of decisions addressing a suite of technical, economic and social concerns. This paper offers a common framework and terminology for describing decision support approaches, along with an overview of recent applications of decision support tools in Europe and the USA. A common problem with work on decision support approaches is a lack of a common framework and terminology to describe the process. These have been proposed in this paper.

## 1. INTRODUCTION

The NATO/CCMS Pilot Study on Remedial Action Technologies for Contaminated Soil and Groundwater Phase 3 is a multi-national forum for the exchange of information on emerging remediation technologies and technology demonstration. The Pilot Study is an activity of NATO Committee on Challenges for Modern Society (Web site: *http://www.nato.int/ccms/info.htm*). The Pilot Study has decided to hold a special session on the subject, which is the third in a series of special sessions. Previous topics were treatment walls (USEPA, 1998a) and monitored natural attenuation (USEPA, 1999).

This paper has been produced for the NATO/CCMS Pilot Study Special Session on Decision Support (June 2000). The session was organized by Brookhaven National Laboratory (USA) and r³ Environmental Technology Ltd. (UK) on behalf of the US Environmental Protection Agency and the Environment Agency of England and Wales, respectively.

This paper also draws upon work carried out by CLARINET, the Contaminated Land Rehabilitation Network for Environmental Technologies in Europe. CLARINET is a Concerted Action within the Environment & Climate Program of the European Commission DGXII (web site: *www.clarinet.at*). CLARINET is a research network for soil and groundwater protection; risk assessment; remedial technologies; and decision support issues including socio-economic and political aspects. CLARINET includes a Working Group (WG2) specifically addressing decision support issues. WG2 has conducted an extensive survey of CLARINET countries to review both key factors for decision support and risk management, and to identify decision support approaches, which it is cataloguing in a *Microsoft Access* database. CLARINET is also developing a range of decision support concepts and plans a web based contaminated land information system, if funding can be secured.

## 2. BACKGROUND

Several billion EURO are spent in the EU, as are several billions of dollars in the USA each year on remediation of land affected by contamination. Decision making, in the face of uncertainty and multiple and often conflicting objectives, is a vital and challenging role in environmental management that affects a significant economic activity. Although each environmental remediation problem is unique and will require a site-specific analysis, many of the key decisions are similar in structure. This has led many countries to attempt to develop standard approaches. As part of the standardization process, attempts have been made to codify specialist expertise into decision support tools. This activity is intended to facilitate reproducible and transparent decision making. The process of codifying procedures has also been found to be a useful activity for establishing and rationalizing management processes.

The uses envisaged or desired for decision support include:

- Identifying realistic management choices;
- Integrating information into a coherent framework for analysis and decision making, discerning key information that impacts decision making from more basic information;
- Providing a framework for transparency (i.e., all parameters, assumption, and data used to reach the decision should be clearly documented) and ensuring that the decision making process itself is documented.

Decision making for environmental contamination problems involves integration of knowledge from many disciplines. There is also a range of contexts in which decisions have to be made, for example compliance with a regulatory need, enabling redevelopment, reducing liabilities, registering and mapping sites, and/or prioritizing use of resources. Each has its own suite of decisions. For example, consider the suite of decisions that have to be made when considering remediation as part of a redevelopment process for a particular site.

- In a typical analysis, the first step in the process is to collect information about the site such as location of spills or disposal areas, the type of contamination that can be expected and the amount of contamination (area, volume, or concentrations). Based on this information, decisions pertaining to collection of site-specific data on the nature and extent of contamination must be made. These types of decisions include the number, frequency, and location of samples balanced against the cost of collecting and analyzing the samples and the value of additional data in arriving at a more robust decision.
- Based on the initial site characterization data, interpolation, extrapolation, and other modeling techniques are often used to estimate the contamination levels between measured data locations. This information is often used in human health risk assessments to guide decisions on the need for remedial action (including monitored natural attenuation). If remedial action is required, decisions pertaining to what regions to treat and what level of remediation is technically and financially achievable must be addressed.
- Projections of contamination levels often have a high degree of uncertainty (i.e., only a few data points are available for estimating contamination over large regions). This uncertainty requires a decision on whether more data is needed to better define the region requiring remediation or to improve the remedy selection or remedy design.
- After remedial actions are complete, monitoring is often required to demonstrate the effectiveness of the remediation. This requires further decisions on what and where to monitor, and the duration of monitoring. A similar list of questions could be generated for other management processes or functions, such as prioritizing development of several contaminated sites or assessing financial risks for sustainable development.

It is unlikely that any single person will have the knowledge to perform all of the analyses required in supporting all of the decisions pertaining to the management of land contamination. Typically, a number of people with different areas of expertise are involved in interpreting basic information and providing it in a form useful for others with less expertise in a given area. It is also apparent that there are many specialist underpinning decisions (e.g., what risk levels are acceptable, what to sample, when to sample, what technologies should be used, etc) that need to be made before general decisions on the reuse of contaminated land can be made. Table 1 lists some of the supporting secondary decisions that need to be made to make the overarching decision on contaminated land management. Table 1 is meant to be illustrative rather than exhaustive.

The range of decisions and their inter-relationships lead to a great variety of decision support approaches. CLARINET WG2[1] has found that these address different management problems, different segments of each problem, and that they operate on a variety of scales and complexities, using a variety of analysis and techniques. The broad range of decision support tools available in the USA has been reviewed by Sullivan *et al.* (1997, 1999-2000), and new methods are regularly announced on the US Environmental Protection Agency's (US EPA) "TechDirect" service[2]. The language used to describe decision support methods has not been found to be consistent by these studies. A common terminology (as far as such a thing is possible), and a general conceptual framework for describing decision support methods, would greatly assist comparisons of methods and their applications, particularly in an international context.

**Table 1. Example issues to be addressed in evaluating remedial requirements and technologies for a site. (Bardos *et al* 2000)**

| ***Category*** | ***Example Issues*** |
|---|---|
| Risk Management | • What risks may be posed by the contamination now and in the future (considering the sources, pathways and receptors and the significance of any linkages found)?<br>• What risks may result to workers as part of the remediation effort?<br>• For affected aquifers: their use and importance<br>• How can the risks best be managed?<br>• What are the regulatory criteria?<br>• What are the success criteria for the proposed remediation?<br>• Fate of contaminants<br>• Is there contamination entering the site from outside? |
| Technical Suitability / Feasibility | • What specific contamination properties need to be addressed (e.g., free-phase organics, concentration ranges, speciation, sorption, toxic by-products, etc.)?<br>• How will remediation performance be measured?<br>• The availability and suitability of existing information for the site<br>• What time-scale is appropriate for remediation? What is the site availability for remediation works?<br>• What is the size of the site? What space is available for remediation operations?<br>• What are the current uses of the site?<br>• Ground conditions (materials, surface conditions, geology) |

[1] Publications on this subject are forthcoming from CLARINET in the next 12 months and will be announced on its web site: www.clarinet.at
[2] Information on TechDirect is available at www.clu-in.org

| | |
|---|---|
| Technical Suitability / Feasibility (cont'd) | • Does the remediation need to cope with underground structures and/or work under buildings?<br>• Hydrogeology and groundwater monitoring<br>• Site access, security, services and facilities |
| Stakeholders' / Third Parties' views | • What are the adjacent properties, who owns them and how are they affected?<br>• How will stakeholder communication be managed?<br>• What impact will the remediation have on site occupants and neighbors?<br>• Restrictions: e.g., planning, covenants, other contract terms, confidentialities |
| Sustainable Development | • What impact will remediation have on other environmental compartments and are these acceptable (wider environmental value)?<br>• Wider economic value<br>• Wider social value<br>• Use of resources, including land resources, for example: what in relation to the long-term use of the site and how this is to change |
| Costs | • Capital and operating costs<br>• Balance of costs to benefits / cost-effectiveness<br>• Funding<br>• Restrictions: insurances, liabilities, securities |

## 3. WHAT CONSTITUTES DECISION SUPPORT - TERMINOLOGY

The dictionary definition of "decision" is: "the act or result of deciding; the determination of a trial, contest or question". The dictionary definition of "support" includes, amongst other things: "to furnish with necessaries, to provide for, to give assistance to, to advocate, to defend, to substantiate, to corroborate". So for the purpose of providing clarity "decision support" can be defined as: the *assistance for, substantiation and corroboration of, an act or result of deciding; typically this deciding will be a determination of an optimal or best approach*. Although obvious, it is important to point out that decision support is NOT the same as taking a decision. The actual *deciding* has to remain the shared responsibility of those with a legitimate stake in the outcome of the decision, i.e., the *stakeholders*. Stakeholders typically include any individuals or groups that may be affected by the environmental contamination. Stakeholders include federal, state, and local regulators, local businesses, citizens, citizen groups, problem holders, environmental industry, and public health officials (PCCRARM, 1997; SNIFFER, 1999).

Another important point pertaining to decision support is that it can come in the form of written guidance or in the form of software. Written guidance is frequently provided by regulatory agencies as a means of obtaining a standardized, reproducible approach to reaching a decision. Most regulatory agencies view written guidance as an essential part of the approach to contaminated land management. In many cases, this guidance is translated into computer software to assist in the calculations (e.g., risk assessment). Software tools are also developed to assist in the decision process for computationally intensive analysis, e.g., flow and transport, geostatistical modeling, and multi-criteria analysis.

The following words are often used in the context of decision support for contaminated land management: *map*, *technique*, *tool*, *tree* or *system*, e.g., "decision support tool", "decision support system". This list is not necessarily exhaustive, and in general, the current usage outlined in Table 2 is useful and efficient.

**Table 2. Terms Used in Decision Support**

| Term | Contemporary Usage | Dictionary Definitions (UK) |
|---|---|---|
| *Map* | A figurative illustration of decision processes, the route taken for a decision | *A delineation: To arrange or plan in detail.* |
| *Roadmap* | A diagram showing the major steps in reaching a decision. | *Colloquial: A detailed plan for achieving specified objectives.* |
| *Technique* | A principal, series of operations used to assist decision making | *A mode of artistic performance or execution, a mechanical skill in art, craft etc* |
| *Tool* | A document or software produced with the aim of supporting decision making, i.e., something that carries out a process in decision support | Includes *anything used as an instrument or apparatus in one's occupation or profession* |
| *Tree* | A logical progression of decision making steps | *A diagram with branching lines* |
| *System* | Variable: for some people "system" is synonymous with "tool" above, for others "system" conveys the entire approach to decision making, including all its components. For them this totality is the decision support system, and something that deals with just a component part would be a "tool" rather than a "system" | *Co-ordinated arrangement; organized combination; method; a co-ordinated body of principles facts, theories doctrines etc; a logical grouping; an organized combination of things working together performing a particular function; any complex and co-ordinated whole* |

"System" is a particularly problematic word, in that it is used to refer to both a component part of the overarching set of decisions necessary, or the whole, both of which are in line with the dictionary definition. However, for the purposes of clarity, it is necessary to select just one of the two alternative meanings for "system", even although this is more limiting than English language usage. Thus, "system " conveys the *entire* decision making approach, including all its components. The reasons for this selection are that: (1) "tool" already conveys the *component part* definition, and (2) there are those who believe that general rules can be drawn up for the overarching system, and not just its component parts.

## 4. THE PROCESS OF DECISION SUPPORT

Decision support methods codify expert knowledge and know-how into a "stored" method or process. The “stored” process could be written guidance on how to address a problem or software that helps to analyze the problem. When addressing a contaminated land management problem, the decision support methods use problem specific information; with the aim of providing a concise representation of the key decision making issues for that particular problem. Hence, decision support integrates information to produce usable knowledge, as illustrated in Figure 1. For example, consider the decision to select between two different remedial alternatives. The analyst would start with knowledge about the nature and extent of contamination. This information would be used to estimate the volume requiring treatment based on the "stored" knowledge (e.g., best practice, regulatory limits, cost data, data management and analysis techniques including interpolation, etc.). This information could then be used as the basis for the selection and/or design of the remedial options. For example, "stored" information on typical remediation costs could be used to estimate likely project costs. Other knowledge such as the degree of uncertainty in the volume requiring remediation and the reliability of the different remedial options could also be evaluated. The decision maker would then be presented with information on costs, probability of success, and what is being treated for the money spent to support the decision on a course of action.

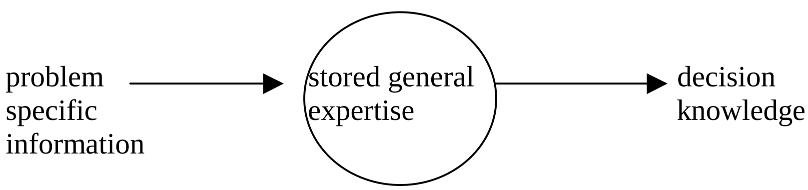


**Figure 1. Illustration of Decision Support**

Decision support methods help to make the decision making process transparent, documented, reproducible, (hopefully) robust and provide a coherent framework to explore the options available. Figure 2 illustrates the stages used to arrive at decision support knowledge for a typical site.

The starting point is to define the objectives for contaminated land management and the constraints on how to manage the land. For a single site, the objective may be to remediate the land to a levels that is acceptable for residential use. For a series of contaminated sites, the objective may be to prioritize which sites to remediate first to minimize risks while maximizing the amount of land available for use. In both cases, the constraints could be time, budget, technical feasibility, and public acceptability. Decision support can then assist the identification of the optimal way to meet the objectives within the constraints. The stages of the decision support process are confined within the dotted lines of Figure 2. Taking the decision is illustrated as being supported by the process. The first stage in the decision support process is to use experience and site-specific information (for example relating to the source terms, pathways and receptors) and site-specific data (for example, soil properties and hydrology). The second stage uses this information to develop simple conceptual models of the site behavior. The conceptual model is the basis for the analysis (third stage in the process), which combines information on the technology being proposed (if any) and the information used to form the conceptual model. Often all of this information is processed in computer software. There are several reasons for the use of software. First, the sheer amount of data in many problems favors electronic storage and manipulation. Second, the complexity of the analysis (e.g., geostatistics, groundwater flow, and transport, human health risk assessment) requires many calculations, which can easily be done on a computer. Third, the use of computers permits rapid evaluation of the effects of changing parameters or scenarios. This may permit uncertainties to be addressed. One perceived limitation of computers is that people tend to accept computer output as being correct and therefore not examine the underlying assumptions. A caveat applies to all computer-generated output; the output is only as good as the data and modeling assumptions used by the software.

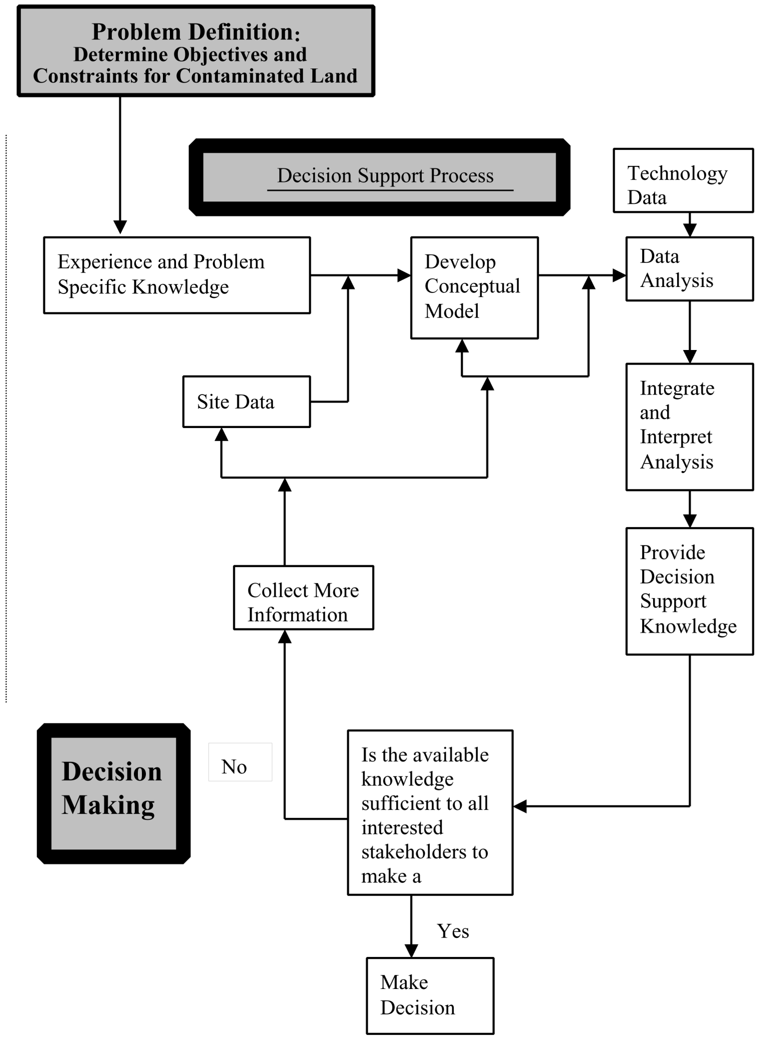


**Figure 2. Flow chart containing the key steps in the decision support process**

For example to determine the effectiveness of different remedial options, estimates of contaminant concentrations before and after remediation may be determined through a combination of data, geostatistical interpolation and flow and transport models. Usually this information has to be interpreted and analyzed in terms of the decision variable (fourth stage in the process). In this example, the contaminant concentrations can be compared to regulatory thresholds and the region that exceeds the threshold can be defined for each remedial option. The computer software may facilitate the interpretation and analysis, but it is the responsibility of the analyst to insure that the analysis is accurate and the output is in a form useful for decision making.

The knowledge supplied to the decision makers (fifth stage) should be transparent and readily understandable by different stakeholders, not just specialists. Indeed, even specialists might struggle with the sheer volume of detail that arises from many sites, and so require some form of rational abstraction of information into a more manageable volume and level of detail. These five stages form the basis for decision support, which uses information abstracted from other (and often more detailed) analyses.

Decision knowledge is supplied to the decision makers, who then evaluate whether all stakeholders agree that the information provided is sufficient to support a decision. All environmental decisions are made with some degree of uncertainty. Complete knowledge is never available or attainable. If the stakeholders conclude that a decision cannot be made, they may request additional data, improved conceptual models, consideration of different technologies or refined analysis. The process of providing decision support is repeated with the new information until a decision can be reached. In some cases, it may not be possible to get all stakeholders to agree to an approach. When this occurs, the process may be vulnerable to litigation.

There is an element of choice in which stakeholders to involve, from those possible (outlined in Section 9). However, some, for example, the regulator, will be an obligatory consultee. There is a difficult balance to be drawn between who to involve and who not to involve. Involving a larger number of stakeholders in decision making will add to the costs, complexity and duration of decision making. However, there is a quid pro quo, in that this involvement may save future difficulties that might be caused by the reactions of aggrieved stakeholders who were not consulted early enough.

Figure 2 also includes the idea that using models is **not the same** as decision support. Rather using models, and modeling techniques and software, is a step in information collection that precedes decision making. It is the integration of model results and their interpretation in terms of the decision variable that supplies decision support. This is an important distinction and is made on the basis that *decision support implies making usable information available to a variety of stakeholders*. A variety of stakeholders may play a role in contaminated land decision making. For example, land owners/problem holders; regulators and planners; site users; those with a financial connection to a site; the neighbors to a site including the local community; the consultants, contractors, researchers and vendors involved in designing and implementing the remediation. In some cases, advocacy groups and pressure groups may also seek involvement. Clearly, it would be an unlucky site manager who had to defend his decision making against all of these stakeholders simultaneously, but any decision made should be clear to them. In particular the site owner and a busy regulator, dealing with a variety of issues, not just contaminated land, will want *reliable* information that can be *easily and quickly* understood.

Figure 3 shows a conceptual framework for information use in decision making and emphasizes that the “system” is the totality of the decision process. In this framework, models are not considered as decision support, but rather as input. Tools, techniques, trees and maps can represent one or more component parts of the decision making process, whereas a "system" supports the totality of a particular decision making process.

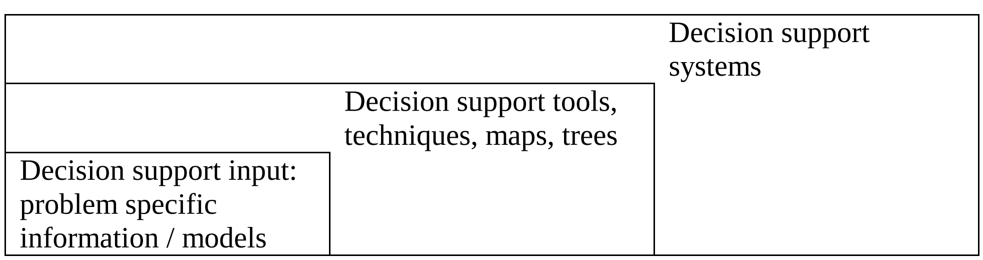


**Figure 3. Decision Support Information, Tools and Systems**

Decision support exists within three broad sets of boundaries: the range of technical possibilities; the level of detail that is appropriate and the legislation and regulations pertinent to the decision. An effective decision support tool needs to offer options that are both technically and economically feasible and permitted by regulators, the public and other stakeholders. In a practical sense, it is equally important that the level of detail is appropriate. The level of detail provided to the decision-makers must be sufficiently explanatory, but it must also be readily understood (as pointed out above). The implications of excess detail are not only reducing the helpfulness of the decision support, but also increasing the cost of the decision support knowledge.

## 5. TYPES OF DECISION SUPPORT

Contaminated land management involves a series of decisions, as management for a particular site progresses. Decision support methods can play a role at each stage of the contaminated land management process: as a decision support *tool*, for specific issues and, in the view of some commentators, over the entirety of a management problem, as a decision support system.

Types of management problems might include: dealing with a contaminated site; prioritizing a number of contaminated sites; or setting an overall sustainable development strategy for contaminated land management in a particular region. For each problem-solving role, different functional applications for decision support can be discerned. For example in managing an individual site, decision support might be required for: site investigation, risk assessment, risk management, aftercare, monitoring, evaluating wider impacts (environmental economic etc) and sustainability appraisal. In a broad sense, these are management steps separated by decision making; for example an appreciation of risk (assessment) leads to decision making for risk management. Within each management step more detailed information will be processed by specialists, for example engineers designing and implementing a remedial system; of life cycle assessment specialists carrying out an appraisal of the wider environmental impacts of competing remedial systems. Translation of the outputs of their work into decision-making knowledge constitutes the role of decision support.

## 6. CATEGORIES OF DECISION SUPPORT

CLARINET has been using four categories to describe decision support tools and other approaches:

- The decision making role of the approach,
- Functional application, i.e., the contaminated land management application
- The analytical techniques used in the decision support approach
- The nature of the decision support product

The decision making role describes the type of decision making being supported, e.g., for managing a single site, or for prioritizing a number of sites. This deals with the overarching decision being made at the site.

The functional application to contaminated land management describes whether the decision support is for risk management, remediation, monitoring and aftercare, sustainable development etc. This deals with the issues that must be addressed to support the overarching decision.

Several different techniques can be employed to assist environmental decision-making. Pollard et al (1990 identified the following: life cycle analysis (LCA); environmental risk assessment (ERA); environmental impact assessment (EIA); cost benefit analyses (CBA); multi-criteria analysis (MCA); multi-attribute analysis (MAT); environmental audit; and sustainability appraisal. In practice, many decision support tools use several of these techniques, or mixtures of different parts of them

The nature of the product describes whether the tool is written guidance; a "map" of some sort, a series of procedures or a software based system. In practice, a number of decision support tools (DST) address multiple decision criteria. For example, software tools might combine risk assessment and cost-benefit analysis techniques to generate risk maps, cost comparisons between remedial options and other decision information.

This framework is summarized in Table 3.

**Table 3. Categories for Decision Support Tools**

| Problem Solving Role | Functional Application | Analyses Used | Nature of the Product |
|---|---|---|---|
| Identification - of problem sites<br>Prioritization<br>Comparison – of options<br>Strategy development<br>- policy<br>- site specific | Problem Identification<br>Site investigation<br>Risk assessment<br>Risk Management<br>Aftercare<br>Monitoring<br>Evaluating Wider Impacts (environmental economic etc)<br>Sustainability appraisal | Risk Assessment<br>Cost benefit<br>Life Cycle<br>Multi-criteria analysis | Written guidance<br>Model procedure<br>Software |

In practice many DST use several analytical techniques, or mixtures of different parts of them. The most commonly applied technique in contaminated land management is environmental risk assessment (see Section 8). Cost benefit analysis (CBA) often in conjunction with multi-criteria analysis (MCA) is increasingly being applied to decision making for remedial option selection once risk based objectives for a problem site have been decided. MCA is briefly described in Appendix 1.

Interest is growing in Europe in also considering the broader impacts of remediation, in the context of sustainable development. For example, LCA techniques have been applied to considering wider environmental impacts in the Dutch "REC" system (NOBIS 1995a; 1995b).

MCA approaches have been considered in the UK for the same purpose. One possible qualitative approach is to assess "wider environmental value" (WEV) in a way that makes use of the views of different stakeholders. Three features of this approach are (i) its use of layered sets of choices to remove potential decision making conflicts, (ii) the recording of these choices as individual rankings which are combined to provide an overall ranking at the end of the assessment process; and (iii) and consulting more than one stakeholder to gain a degree of objectivity in the rankings. The general assessment steps that might be included in such a framework are presented in Table 4 (Bardos *et al* 2000b).

The involvement of different stakeholders (e.g., Consultant, community, regulator, problem owner) in a consistent decision making process is increasingly seen as being important (Pollard *et al* 1999; ESRC 1997, PCCRARM 1997. USEPA 1995, USEPA, 1998b). Decision making also has to encompass an increasing range of viewpoints and disciplines, not just soil science and environmental engineering but also economic, political and social aspects. Environmental decision-making is in its infancy as a general discipline, and so current approaches tend to be fragmented and overlapping (Pollard *et al.*, 1999; Tonn *et al.,* 1999).

**Table 4. An approach to assessing wider environmental value.**

| Step | Action |
|---|---|
| 1 | Determining the objectives of the assessment |
| 2 | Identifying the stakeholders for consultation |
| 3 | Determining the scope of the assessment (i.e., which components should be included and their basis for assessment) |
| 4 | Determining the boundaries for the assessment |
| 5 | Making a comparison of WEV for an existing shortlist of remediation techniques (using an modified MCA approach) |
| 6 | Refining comparisons and testing sensitivity to changes in input values |
| 7 | Interpretation |

## 7. OVERVIEW OF DECISION SUPPORT APPROACHES CURRENTLY IN USE IN EUROPE AND THE USA

The concern over potential human health effects resulting from poor environmental practices and the limited amount of clean land in economically desirable areas has led to the growing need to evaluate the extent of contamination and remediate as necessary. The magnitude of these problems has caused many countries to examine these problems on a national basis to develop priorities for sustainable development. The management of contaminated lands must support multiple goals that are often conflicting. That is the management decisions must be protective of human health while making appropriate use of economic resources and supporting sustainable development.

The large number of contaminated land problems with similar characteristics has led to several attempts to develop tools (DST) that support the wide range of decisions related to contaminated land management and re-use. One objective of development of these tools is to obtain a consistent, reproducible and transparent approach to supporting decisions. Another objective is to provide a consistent methodology to compare contamination issues at different sites and serve as a basis for setting priorities.

CLARINET WG2 has found that for evaluation of contamination at a single site, there is a general commonality of approach that is emerging internationally, albeit with some differences at the operational level. A similar set of management tasks has been identified for dealing with land contamination, which typically include:

a. problem identification (including historical assessment and as a result the identification of potential sites);
b. problem investigation determination of the need for remediation;
c. risk identification (actual and potential);
d. detailed risk evaluation and the identification of the remediation goal;
e. selection and implementation of remedial measures;
f. monitoring of sites following remediation.

Although these tasks have been listed sequentially, in practice efficient implementation of the process often involves feedback and iteration between them. Recently, in the USA, there has been an emphasis on using a three step process involving systematic planning, dynamic work planning and on-site analysis to assist technical decision making at a contaminated site (Crumbling, 2000). In this approach, data (for characterization or monitoring) are analyzed on-site, risk assessments are updated based on the new data, and the need for additional samples is evaluated and the work plan is altered to reflect the most recently available data. The approach is intended to provide a more efficient characterization and better technical support for decision making as compared to following steps a-f in a sequential manner.

Whilst this forms the broad skeleton of many flow diagrams, the actual flow diagrams are frequently more complex when applied to specific problems or sites. In fact, DST are often used to support all steps of the contaminated sites management process (from investigation through remediation and monitoring), with different DST applied to different steps or groups of steps. A few examples of these types of applications include:

- providing a visual depiction of the extent of contamination as a means of highlighting areas of concern (problem and risk identification);
- providing a technical basis for sample selection based on the existing data and the probability of exceeding a regulatory limit (problem investigation);
- defining the volume of remediation required as a function of the confidence in meeting regulatory goals (For example, one could remediate only at sample locations that are above the limit. In this case, one would have little confidence that the entire site is clean. On the other hand, one could remediate the entire site if any single measured value was above the limit. This would lead to high confidence that regulatory goals were met, but would be very expensive in most cases).
- providing estimates of current and future human health risks as a function of the amount of remediation (detailed risk evaluation);
- providing cost-benefit analysis between competing remedial technologies (selection and implementation of remedial measures); and

Overarching decision support *systems* include the "Model Procedures", written guidance under development in the UK (DETR and Environment Agency 2000). Overarching decision support systems remain the goal of a number of decision support software development teams.

The preceding examples focused on addressing issues at a single site. DSTs are also used to address problems at multiple sites. For example, life cycle cost analysis tools are useful to examine a range of problems and to identify the problems with the largest life-cycle costs and the areas that lead to the greatest costs. This can be used as one basis for identifying areas of opportunity to reduce costs.

DST has also been used to support litigation. Litigation often occurs when the responsible party is difficult to ascertain due to complex geology or multiple sources. In these cases, DST have been used to analyze the data using detailed technical models, abstract and interpret the model output to address the technical questions, and present this information (often through visualization techniques) for use by a non-technical audience (judge and jury) (Green, 2000).

To some extent, this commonality of approach in contaminated land management should not be surprising. The nature of the basic steps of evaluation and remediation are determined by the practicalities of contaminated site management, which of course is not country dependent. Decision making in many countries is now increasingly seen as seeking a balance between “cost” and “benefits”. ‘Costs’ are increasingly seen from an environmental as well as an economic perspective. In all countries, resources are limited so remediation work must show a clear balance of benefits over costs.

## 8. RISK-BASED DECISION FACTORS

### 8.1 Human Health

Human health risks that may be caused by contamination are becoming a primary basis for supporting decisions on remediation throughout the EU and the USA (USEPA, 1989, USEPA, 1996a; USEPA, 1996 b; CLARINET and NICOLE, 1998, Ferguson *et al* 1998, Ferguson and Kasamas, 1999). In this process, risk assessment and the subsequent step of risk management are intimately related elements that form the basis for decisions on the fitness-for-use approach to land affected by contamination. The goal of risk assessment is to provide an objective, scientific evaluation of the likelihood of unacceptable impacts to human health and the environment. The goal of risk management is to support decisions on risk acceptability for specified land uses and to determine the actions to be taken. It is the process of making informed decisions on the acceptability of risks posed by contaminants at a site, either before or after treatment, and how any needed risk reduction can be achieved efficiently and cost effectively (Ferguson *et al* 1998, Ferguson and Kasamas 1999). In this way, the over riding needs for the protection of human health and the environment can be clearly identified and work prioritized accordingly.

The assessment and management of land contamination risks considers three main elements, as illustrated in Figure 4:

- the source of contamination (e.g., a solvent spill, or buried materials on a redevelopment site)
- the receptor (i.e., a part of the ecosystem that could be adversely affected by the contamination, such as groundwater, human beings, flora and fauna)
- the pathway (the route by which a receptor could come into contact with the contaminating substances).

A hazard exists when contamination exists: i.e., a source of toxic substances. A hazard is a situation in which contamination in the ground has the *potential* to cause harm (e.g., adverse health effects, groundwater rendered unfit for use, damage to underground structures, etc.) to a particular receptor. Risk is commonly defined as the probability that a substance or situation will produce harm under specified conditions. Risk is a combination of two factors, the probability of exposure multiplied by the consequence of exposure (PCCRARM, 1997). Risk occurs when all three components are present (a source, a receptor and a pathway for that receptor to be exposed to the toxic substances from the source). Thus, if a hazard exists and there is a chance that a receptor will come in contact the hazardous material through any pathway, a risk exists.

The presence of all three elements is also referred to as a pollutant linkage. Risk assessment involves the determination and characterization of such a relationship, including for example, delineation of the source, measurement/modeling of fate and transport processes along the pathway, and the potential effect and behavior of the receptor. A consideration of risk must also take account of not only the existing situation but also the likelihood of any changes in the conditions in the future.

Risk management is the art of managing environmental contamination so that the risks posed by contamination are controlled or reduced to levels agreed upon by the regulators, problem owners, and other stakeholders. Risks should be assessed on a site-by-site basis to ensure that a site is suitable for its designated use.

**Figure 4. A Pollutant Linkage**

### 8.2 Ecological Risks

In the United States and Europe, there has been a recent trend to include ecological risks as a decision variable for contaminated land management. The process of ecological risk assessment follows the same paradigm as human health risk assessment with the exception that the receptors are the plants and animals that inhabit the site. For example, guidance on which receptors should be considered in ecological risk assessment (USEPA, 1997, USEPA, 2000) and how to manage ecological risks (USEPA, 1999) has been published in the USA and the Netherlands (Ferguson *et al* 1998, Rutgers *et al* 2000). In Europe the pollutant linkage paradigm is used to consider human health and risks to other receptors such as ecosystems, groundwater and even buildings.

## 9. Other Decision Making Factors

Although human health risk is the most widely used factor to support decision making, there are a number of other factors that impact the decision process. These include:

- Technical suitability / feasibility
- Stakeholder / Third Party views
- Costs and Benefits
- Sustainable development

Each of these is addressed below.

<u>Technical suitability/feasibility</u>
Suitability is closely entwined with feasibility. Suitability refers to the ability of the technical solution to meet remedial objectives. Clearly, it is not worthwhile to attempt a remedial approach that is not suitable for the risk management problem posed. However, a proposed solution may appear to be suitable, but is not feasible. Factors that might cause concern over feasibility include:

- Track record of the solution for the particular environmental remediation problem ;
- Ability to offer validated performance information for previous projects;
- Expertise of the purveyor;
- Ability to verify the effectiveness of the solution when it is applied;
- Confidence of stakeholders in the solution and in its costing;
- Acceptability of the solution to stakeholders who may have expressed preferences for a favored solution or have different perceptions and expertise.

<u>Stakeholders</u>
The owner of the site is not the only stakeholder in contaminated land management decisions. The principal stakeholders in remediation are considered those with an interest in the land, its redevelopment, and the environmental, social and financial impacts of any risk management activities. Depending on the size and prominence of the site these stakeholders will include several of the following (Bardos *et al* 1999):

- Land owners / problem holders;
- Regulatory and planning authorities;
- Site users, workers, visitors;
- Financial community (banks, funders, lenders, insurers);
- Site neighbors (tenants, dwellers, visitors);
- Advocacy organizations and local pressure groups;
- Consultants, contractors and technology vendors; and possibly
- Researchers (in some circumstances).

Each will have their own perspective, priorities, concerns and ambitions regarding any particular site. The most appropriate remedial actions will offer a balance between meeting as many needs as possible, including also the need to protect the environment, without unfairly disadvantaging any individual stakeholder. Such actions are more likely to be selected where the decision-making process is open, balanced, and systematic. Given the range of stakeholder interests, agreement of project objectives and project constraints such as use of time, money and space, can be a time consuming and expensive process.

A diverse range of stakeholders for example, the site owner, regulators, planners, consultants, contractors, site neighbors and perhaps others, may need to reach agreement before specific remedial objectives can be set. Unsurprisingly once these remedial objectives are set, it may be hard to renegotiate them.

Costs and Benefits

The aim of the assessment of costs and benefits is to consider the diverse range of impacts that may differ from one proposed solution to another such as the effect on human health, the environment, the land use, and issues of stakeholder concern and acceptability in a common units. Deciding which impacts to include or exclude from the assessment is likely to vary on a site-by-site basis. In many instances, it is difficult to attach a strictly monetary value to many effects. Hence, assessments can involve a combination of qualitative, formal CBA and MCA methods. It is also useful to include a sensitivity analysis step, particularly where this encourages decision-makers to question their judgements and assumptions through the eyes of other stakeholders.

Sustainable Development

The concept of sustainable development was first considered at the United Nation's Earth Summit conference in Rio de Janeiro in 1992 A number of definitions for sustainable development have been proposed, a widely used definitions is; "...development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland, 1987). At a strategic level, the remediation of contaminated sites supports the goal of sustainable development by helping to conserve land as a resource, preventing the spread of pollution to air and water, and reducing the pressure for development on green field sites.

Interpreting sustainable development in the context of land remediation is a complex issue and requires guidance on specific components of the decision process, such as the environmental effect of different types of remedial options as well as overall guidance on the whole risk management process. The importance of the environmental effects for each option considered will be dependent on the site itself, for example, nuisance issues (e.g., odors, dust, noise) associated with remedial options for a remote site may be less important than for one in a city center. In addition, the significance of such effects will vary at a local, regional and / or national level.

Combination of Decision Factors

Typically risks to human health risk and other receptors are used as a basis for setting remediation goals. In these cases, other decision factors such as technical feasibility and cost are used to select from amongst different remedial alternatives. In cases when the desired level of protection for receptors can not be attained due to costs or technical difficulties in remediating the site, treatment levels are agreed upon by the stakeholders on a case by case basis. If the risks are viewed to be large enough, extreme measures to reduce the exposure pathway may be taken (e.g., evacuation). If the risks are only slightly above regulatory standards cost/benefit analysis may be used to reach consensus on clean-up standards. For example, in the U.S. there is a screening level for risk such that if the excess human lifetime cancer risk is less than 1 part in $10^6$, no further efforts need to be made to reduce risks. A case can be made to have risk cleanup goals exceed 1 part in $10^6$ if it is not technologically or economically feasible to reduce it below this level. If the risk is too large, for example, if the excess lifetime cancer risk exceeds 1 part in $10^4$ remedial actions are required to reduce risk.

Depending on the problem, any of these factors may become the overriding basis for making a decision. For example, even if a technically feasible solution that protects human health and the environment to within regulatory limits at an acceptable economic cost is available, if the stakeholders do not accept the solution, remediation should not proceed until a solution agreeable to all parties is found. If remediation proceeds, it is at the risk of having substantial opposition that may cause the efforts to be stopped or modified. This can lead to greater program costs. The literature contains several examples where decisions that were acceptable from a technical and regulatory perspective were not acceptable to all of the stakeholders. For example, siting of new waste disposal facilities and the use of the incineration as a treatment option have been prevented because of stakeholder concerns.

## 10. DIFFERENCES IN THE DECISION MAKING PROCESS BETWEEN COUNTRIES

Although there is a general commonality in approach to contaminated land management, differences in the decision making process exists between different countries and even within different regions of the same country. When this occurs, it is, generally because of one or more of the following:

- differences in the applications of general principles (such as which receptors are to be considered);
- differences in the use of analytical techniques, datasets and assumptions;
- differences in priorities for environmental protection;
- differences in administrative approach;
- regional variation in characterization of land, land use, society and economy.

These differences tend to mean that decision support tools intended for an operational application are not always directly transferable from country to country. Another important reason that DST are not always transferable between countries is that unless the tool has received extensive documentation, application, verification testing and peer review in the country its use is proposed in, the quality of the tool for use there may be difficult to judge. Table 5 presents the key transferability issues, providing examples in terms of analysis of soil or groundwater contamination. However, the major issues still apply to other types of analysis (e.g., Life cycle analysis, multi-criteria analysis, etc). To address the issue of quality of decision support software tools, the US EPA extensively tested six different tools on existing environmental contamination problems as part of their Environmental Technology Verification program (Sullivan, 1999a, b; Sullivan, 2000 a,b,c,d).

Differences in applications of general principles can, for example, include whether or not ecological impacts are explicitly included in guideline values. Other differences include the characterization and treatment of uncertainty in the decision process and how end uses are categorized and then considered for risk assessment tools.

**Table 5. Issues in portability of Decision Support software tools**

| Criteria | Issue for Portability |
|---|---|
| Documentation of Models and Assumptions | Are the model assumptions reasonable and appropriate? Analysis of environmental problems requires conceptualization of the 'real world' into a construct that permits analysis using a computer. This conceptualization process involves a number of assumptions. It is important for the models and assumptions to be thoroughly documented to permit an evaluation of the models relevancy to specific problems. |
| Multiple Lines of Reasoning | Can the model address uncertainty in data and model parameters? The variability in natural systems makes analysis difficult. Often, multiple approaches can be used to define the extent of contamination. Models that can easily provide multiple realizations of the problem can help address uncertainty issues. |
| Applications on Similar Problem | Has the model been successfully used for similar applications? Successful application of a tool on similar problems can build confidence in the tool. |
| Validation/Benchmarking | Has the model been validated or benchmarked? Comparison of model predictions with analytical solutions (validation) and predictions of other accepted models (benchmarking) can build confidence in the model. |
| Ease of Use | Is the software easy to use? Some software has features that improve the usability of the product. For example, it is advantageous to use software that allows data to be imported or exported in many formats, to write scripts to perform repetitive tasks, to generate reports to document all model parameters, and to generate hardcopy graphics and visualizations. Software that is easy to use is more efficient at using the analyst's time. |
| Training & Technical Support | Are training and technical support available? Many of the DS tools require specialized expertise (i.e., flow and transport modeling, geostatistics, human health risk). Training and the availability of technical support to address non-routine issues are crucial for effective use of many tools. |
| Efficiency and Range of Applicability | Is the model flexible enough to handle other problems that you might encounter in the future? Some DS tools are limited to specific problems or a narrow range of problems while others can simulate a wide range of problems. The tool must be applicable to the set of conditions anticipated for the analysis. |

Differences in priorities for environmental protection often underpin the differences in end use consideration. A major difference between countries is the way in which groundwater not currently in use is considered as a resource. This can be markedly different for countries depending on their surface water resources. More generally, while there is considerable awareness of the need to address issues of sustainability (wider economic, environmental and social effects), these are explicitly considered only in a limited number of cases.

Differences in regional variations include the extent to which industrialization and industrial change has occurred, the attitude to accepting risks, differing social priorities, and the financial and technical resources that are available to deal with any problems. Both economic factors and the attitude of society to contaminated land problems determine the resources made available.

## 11. CONCLUSIONS

Contaminated land management is an important issue throughout Europe and the U.S.A. The need for developing techniques and approaches to improve the decision making process for reuse and/or remediation of contaminated lands is widely recognized. As a starting point, to improve communication on this topic, the following definition is offered. Decision support can be defined as: the *assistance for, and substantiation and corroboration of, an act or result of deciding; typically this deciding will be a determination of optimal or best approach*. The decision support process integrates specific information about a site and general information such as legislation, guidelines and know-how, to produce decision-making knowledge with the goal of being transparent, consistent and reproducible. The complexity of environmental remediation problems necessitates several layers of decision support including technical decisions on sample collection (how many and where), economic decisions pertaining to are the costs worth the benefits, and social/political decisions on sustainable land development. Each of these layers may need to be addressed as part of the overarching decision on land management and many of these 'layers' are interdependent. In all cases, the decision support process takes basic input information (problem definition); uses decision support tools to integrate, analyze and abstract from the information and provides knowledge directly relevant to the decision. Approaches to contaminated land management have been found to follow a similar broad outline independent of the country where the problem is located.

The large number of contaminated land problems with similar characteristics has led to several attempts to develop tools (DST) that support the wide range of decisions related to contaminated land management and re-use. One objective of development of these tools is to obtain a consistent, reproducible and transparent approach to supporting decisions. Another objective is to provide a consistent methodology to compare contamination issues at different sites and serve as a basis for setting priorities. DSTs have seen widespread use in all steps of the contaminated site management process (from investigation through remediation and monitoring).

Contaminated land management decisions often involve a number of factors. The most widely used decision factor is protection of human health to regulatory prescribed levels of risk. Other factors such as technical suitability and feasibility, cost-benefits of remediation, stakeholder concerns, and long-term sustainability may also be used in the decision process. Often human health risks are used as the basis for setting remedial objectives. In this case, the decision often becomes what technology can meet the health risk goals at the lowest cost while meeting stakeholder concerns. The most appropriate remedial actions will offer a balance between meeting as many needs as possible, including also the need to protect the environment, without unfairly disadvantaging any individual stakeholder.

Despite the similarities between contaminated land problems throughout the world, there are differences in the approach to these problems. These include differences in application of general principles (e.g., some countries consider ecological risk as one basis for analysis while others do not); differences in priorities (e.g., groundwater management is more important to countries with limited surface waters); differences in administrative and regulatory approach; and differences in social attitudes towards risk and the resources available for land management.

## 12. ACKNOWLEDGEMENTS

This work has been supported by the Environment Agency and the Department of the Environment Transport and the Regions (UK), ADEME (France) and Aquater (ENI Group) (Italy).

The authors gratefully acknowledge the views of many from the NATO/CCMS and CLARINET communities, in particular Ian Martin, Joop Okx and Malcolm Lowe, and the agreement of CLARINET to use its material.

The views in this paper are the authors' and are not necessarily those of their employers or sponsoring organizations.

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## APPENDIX: MULTI-CRITERIA ANALYSIS

Multi-criteria Analysis (MCA) is often used in decision making. MCA is a structured system for ranking alternatives and making selections and decisions. Considerations are: how great an effect is (score) and how important it is (weight). A general outline of the MCA method is shown in Figure A.1. MCA goes one step further than a decision matrix by allowing scores to be combined into overall aggregates and allowing scores to be weighted. With MCA, ranking and decision making processes can be made very transparent.

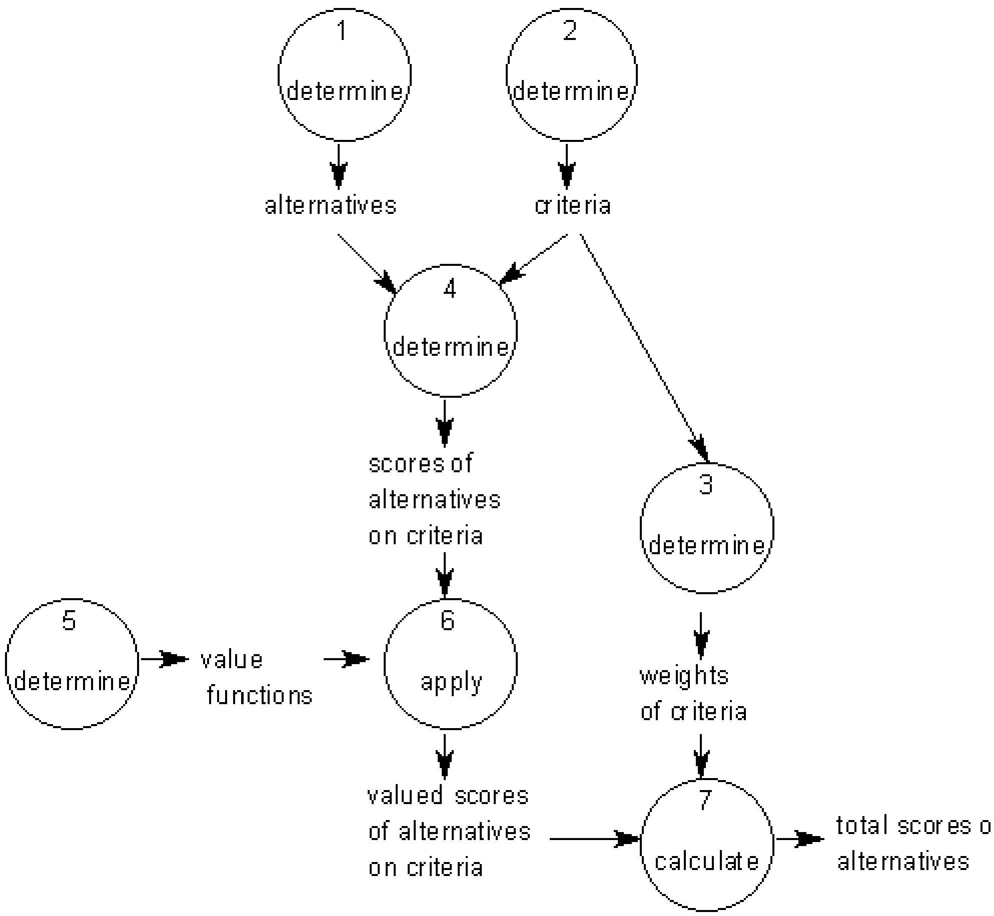


**Figure A.1. A General Outline of the MCA Method**

Taken from: Bardos, R.P., Nathanail, C.P., and Weenk, A. (1999) “Assessing the Wider Environmental Value of Remediating Land Contamination.” Environment Agency R&D Technical Report P238. Available from: Environment Agency R&D Dissemination Centre, c/o WRC, Frankland Road, Swindon, Wilts SNF 8YF.

# GEOSPATIAL DECISION FRAMEWORKS FOR REMEDIAL DESIGN AND SECONDARY SAMPLING

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## INTRODUCTION

This paper provides an overview of geospatially-based decision frameworks for remedial and secondary sampling design strategies. These methods were generated or implemented during the construction of Spatial Analysis and Decision Assistance (SADA), a freeware package for Windows. SADA is supported by the Environmental Protection Agency and the Department of Energy. For more information on SADA or on the methods described here, see http://www.sis.utk.edu/cis/sada/.

Although the remedial design frameworks are quite straightforward, they rely on geospatial and human health risk modeling results that are beyond the scope of this paper. Therefore, this paper only presents how output from the modeling practices can be used explicitly in a decision-making process. Additionally, a general overview of geospatial analysis provides context for the methods. Three remedial design approaches are presented: block scale, site scale, and site-block scale. Each framework has important implications for both risk assessment and remedial design, and in practice each has better defined the area of concern and ultimately saved valuable resources during the remedial process.

Similarly, the sampling designs in this paper rely on the same geospatial models. These secondary sampling designs assume that a round of sampling has already occurred, a geospatial model has been chosen, and a goal for taking another round of samples has been decided. Five distinct sampling strategies are presented, each with a separate goal.

## OVERVIEW OF GEOSPATIAL ANALYSIS

For this paper, geospatial analysis refers to the modeling of concentration values or uncertainty at points that have not yet been sampled. Geospatial models estimate or predict the value of a contaminant at an unsampled point based on nearby sample values, spatial correlation, and a number of other possible parameters depending on the method chosen. These models are often called contouring algorithms and include well-known methods such as inverse distance weighting and minimum tension gridding. Other increasingly popular methods for environmental characterization include ordinary kriging, indicator kriging, and co-kriging. These *geostatistical* methods contour concentration values and also provide a model of uncertainty about those predicted concentration values through the use of spatial covariance models. For more information on this subject, see *Applied Geostatistics*[3], *GSLIB*[4], or *Geostatistics for Natural Resources Evaluation*[5].

In most cases, a geostatistical analysis begins by defining a grid over the site.

[3] Issaks and Srivasta, *Applied Geostatistics*, Oxford University Press, 1990.
[4] Deutsch and Journel, *GSLIB*, Oxford University Press, 1997.
[5] Goovaerts, Geostatistics for Natural Resources Evaluation, Oxford University Press, 1997.

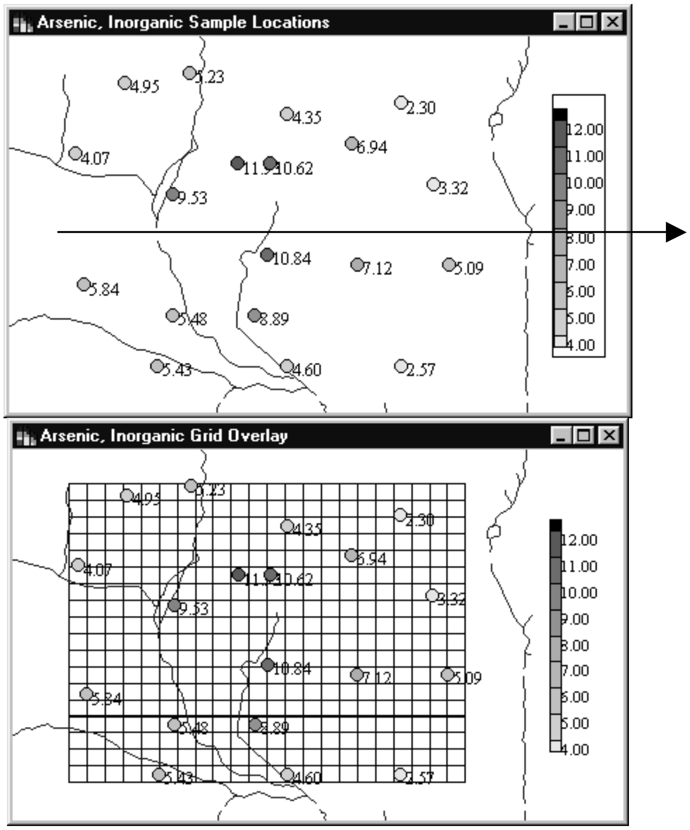


**Figure 1. Defining a grid over a sampled site.**

The blocks formed by this grid become the basis for remedial design and for secondary sampling strategies later. Once the grid is in place, a spatial model is run and the site is contoured.

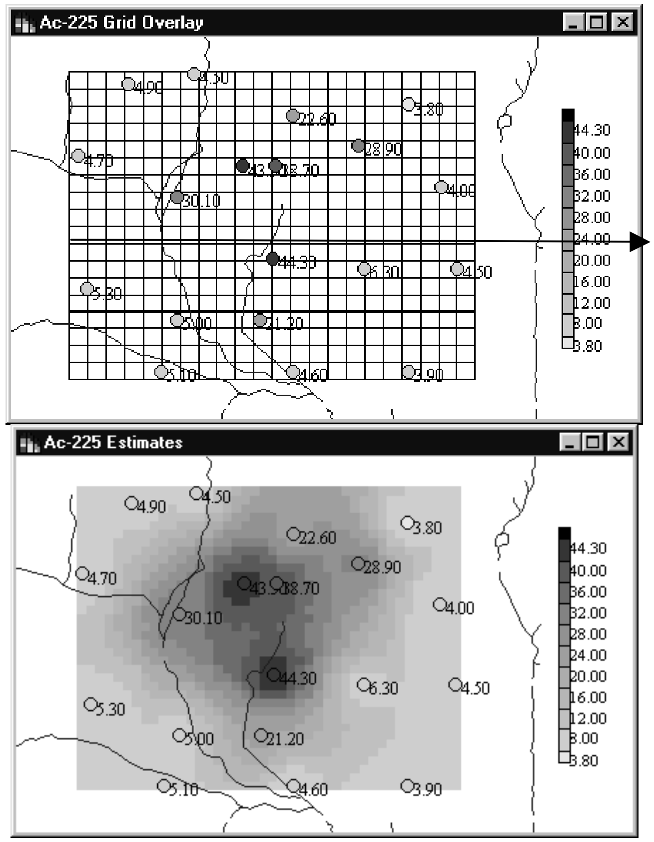


**Figure 2. Contouring a gridded site with a geospatial model.**

## REMEDIAL DECISION FRAMEWORKS

Given a spatial model of concentration values, three frameworks are available for determining the remedial design: block scale, site scale, and the site-block framework. Each framework has a separate objective for remediation, can give a significantly different result depending on the spatial distribution of contamination, and is connected to a decision criteria. This criteria may include a cleanup concentration goal, a human or ecological risk goal, or a state or federal guideline for maximum concentration values. Depending on the geospatial model utilized, other goals may be a part of the criteria, including a confidence level about the remedial design. Once a criteria is available, it is straightforward to implement the following design strategies.

*Block Scale*

In the block scale framework, the decision criteria is applied to each block. In other words, each block must pass the acceptable criteria or be remediated. Choices for the block size include the exposure unit and the remedial unit size.

*Site Scale*

The site scale framework requires a region or subset of blocks to meet the decision criteria. In this case, the blocks may be equal in size to the remedial unit if the region is itself the exposure unit. In particular, if a representative statistical value of the blocks (e.g., average value or mean) fails to pass the acceptable criteria, then remedial action must be taken on the region. Under this system, the blocks are ordered from most to least contaminated. The blocks are then remediated from worst to best until the selected statistical value is below the acceptable criteria. This is a powerful approach that operates nicely under the concept of exposure unit within risk assessment . Under this concept, only the worst blocks are removed until the risk to an individual or species exposed to the entire site or exposure unit area is below a target risk level.

This framework, however, may result in individual blocks exceeding the target risk value. This issue is addressed in the site-block framework.

*Site-Block Scale*
In this approach, there are two decision criteria. The first is the acceptable site value and the second is the acceptable block concentration. First, the site scale is applied to reduce the site wide exposure level to a suitable value. Next, a review of remaining block values is performed to determine if any single block value exceeds the maximum concentration value. If so, the block scale framework is applied until the maximum remaining block value is less than the second constraint. From a risk perspective, this may be the most appealing framework because the exposure unit risk is acceptable and unacceptable hot spots are removed.

Ultimately, this framework is reduced to either the site scale or block scale framework in practice. The site-block framework is effectively the block scale framework when the site scale fails to remediate far enough to meet block scale requirements. Conversely the site-block framework is equal to the site scale framework when enough blocks are remediated such that the maximum contamination remaining also satisfies the block scale framework.

**Example**

Consider the following site contaminated with Arsenic. The human health risk assessment has established that for an industrial landuse scenario, the target carcinogenic risk will be set at 1E-6, corresponding to an exposure value 3.5pCi/g. The following figure shows the location of samples. Those enclosed by boxes exceed the target risk limit.

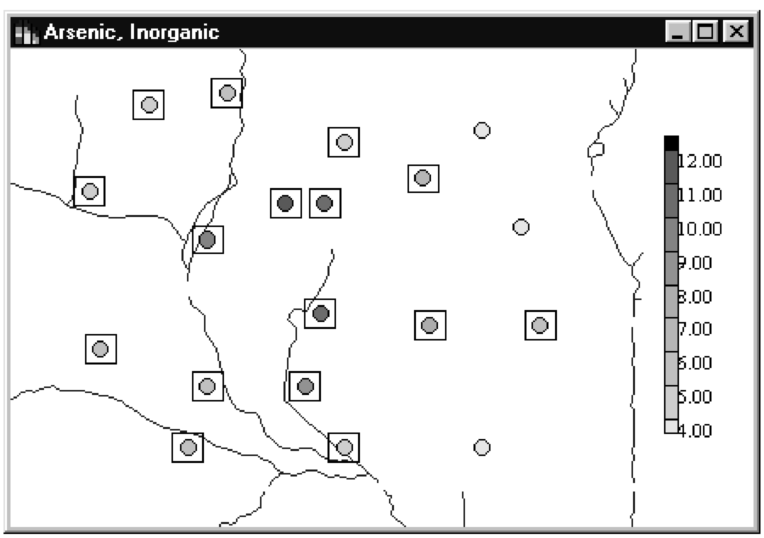


**Figure 3. Location of sample points exceeding acceptable risk level**

Through stakeholder discussions, the value 3.5 pCi/g becomes a cleanup goal. A geospatial analysis is performed on the site, yielding the following contour map.

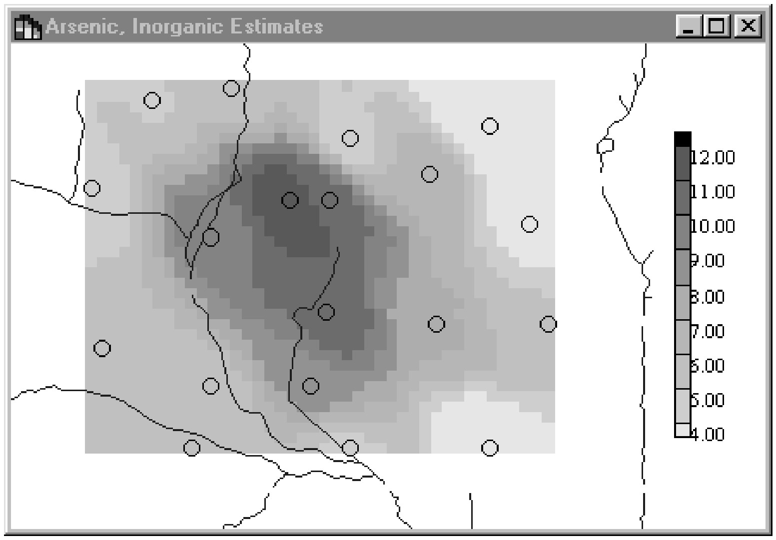


**Figure 4. Geospatial contour of Arsenic concentrations across the site.**

At this point, any of the decision frameworks may be applied. The framework must be chosen with a cleanup goal in mind.

In the block scale framework, any block exceeding 3.5pCi/g will be remediated. The following figure shows the remedial design for this framework. The areas shaded in gray must be remediated.

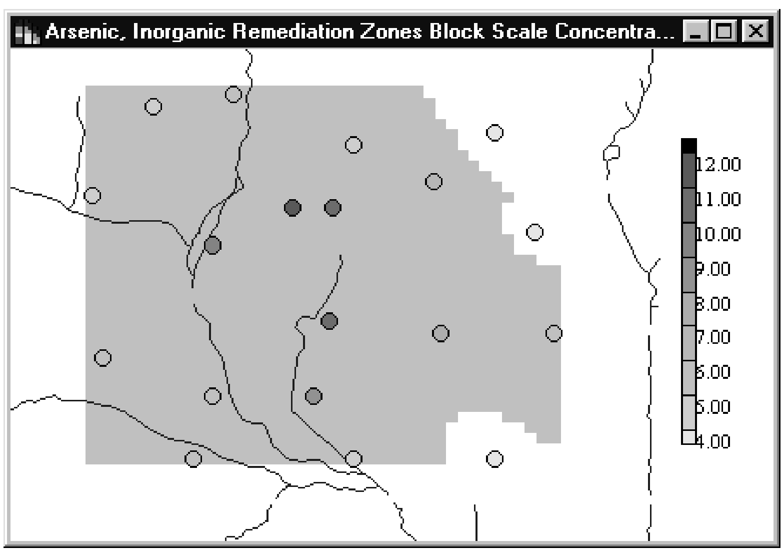


**Figure 5. Remedial zone for the block scale framework.**

Using the site scale framework, the worst areas are remediated until the site average concentration drops below the target risk value. This corresponds to the site-wide risk dropping below 1E-6.

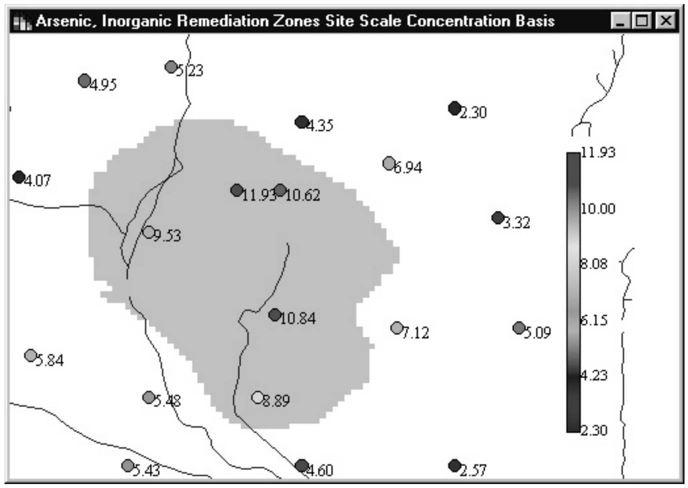


**Figure 6. Remedial zone for the site scale framework.**

For the site/block framework, stakeholders decided that the site-wide risk must be less than 1E-6 risk (which corresponds to a site wide average concentration of less than 3.5pCi/g) and the contamination for each block must be less than twice this concentration value. Thus our site scale goal is 3.5 pCi/g and our block scale goal is 7pCi/g. The site/block framework results in the following design.

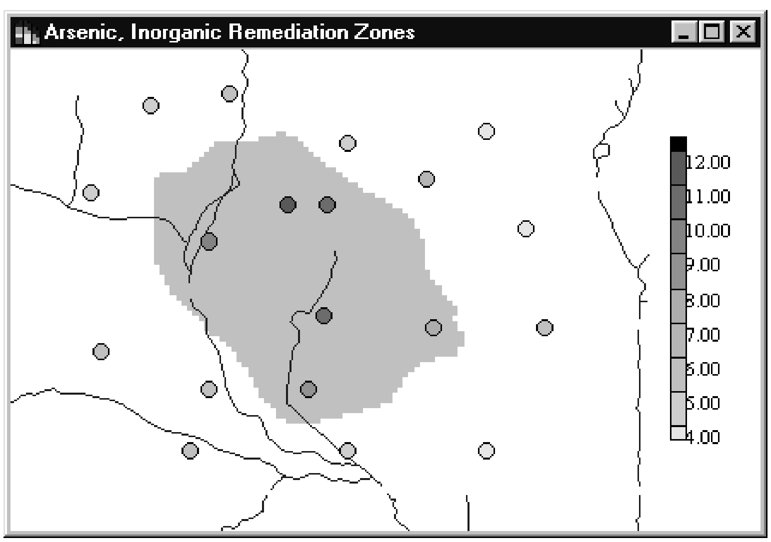


**Figure 7. Remedial zone for the site-block scale framework.**

By comparing Figure 7 with the site scale result for 3.5 pCi/g (Figure 6), the site/block framework is reduced to the block scale with a cleanup goal of 7pCi/g.

**SECONDARY SAMPLING STRATEGIES**

Geospatial modeling routines open avenues into other decision frameworks in sampling design. In a geospatially-based design, the contouring methods provide a model of concentration values or uncertainty at each point across the site. With this result, a suite of sampling strategies is available with unique goals for taking additional samples.

In an ideal situation, the sampling design strategies described here would select a location for a new sample, the sample would be taken, and the result would be analyzed and put back into the model to produce the next optimal sample location. Under this ideal situation, the following sampling strategies could drive a sampling effort in real time. This is possible for sampling devices with quick turn around capabilities and has been a useful option on some sites already.

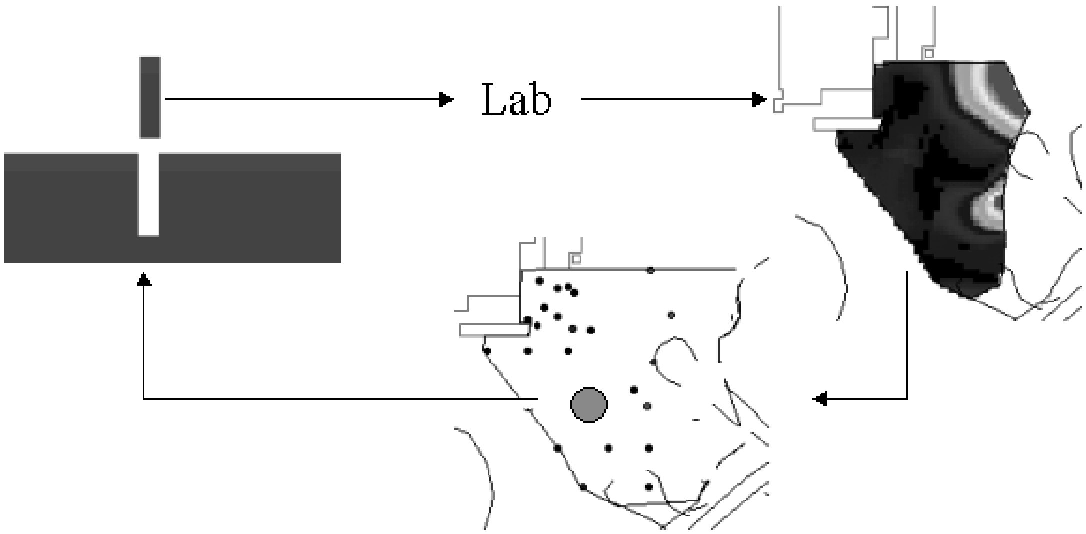


**Figure 8. Flow for chart for using geospatial analysis to drive a sampling design in real time.**

Without quick response time, the method must be able to predict the optimal location of several samples at once. This is achieved with simulated sampling. In other words, if multiple new samples are requested, the most optimal location is chosen first, and a modeled sample value is taken at that point and treated as if it where a true sample. The model is rerun, and the next optimal location is chosen for the second sample point. This is repeated until the number of samples requested is generated. Although the accuracy of each additional request is reduced as more and more dependency is placed on modeled values, this sampling is a valuable alternative when faced with producing a plan for multiple samples at once.

Five sampling strategies are demonstrated on the following sample site. The suggested new sample locations are highlighted with circles. Each block center becomes a candidate for a new sample location.

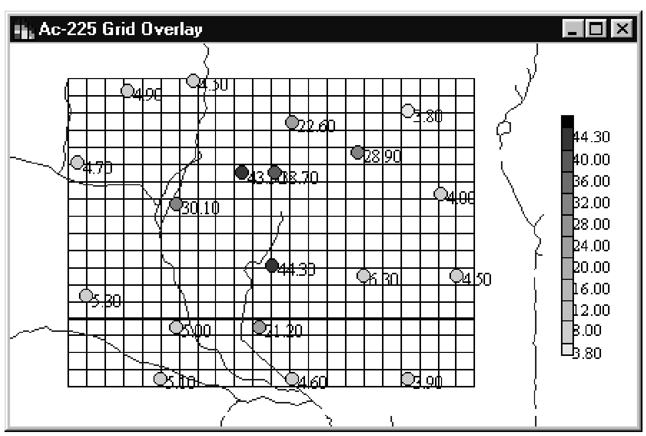


**Figure 9. Gridded site used for building a secondary sampling design.**

*Adaptive Fill*

The goal of this strategy is to fill spatial data gaps by sampling in those areas where data are far apart relative to the rest of the set. It is easy to implement this strategy because it is not dependent on a contouring method.

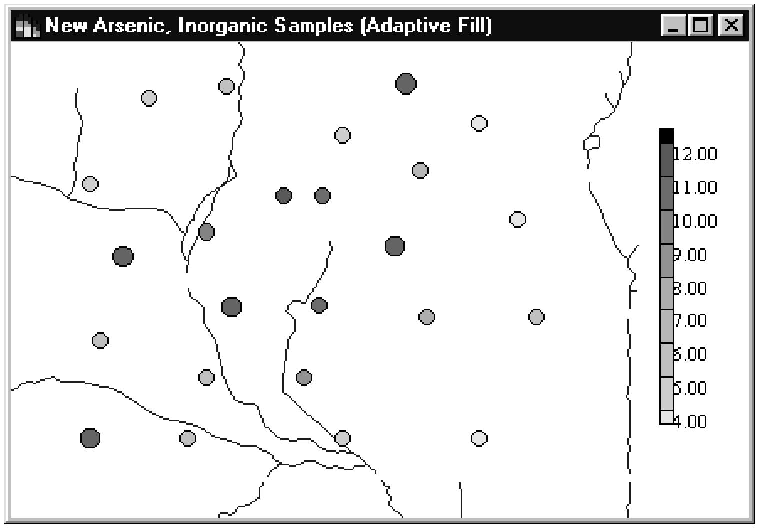


**Figure 10. Adaptive fill results.**

*Estimate Rank*
The goal of estimate rank is to place new sample locations where the highest concentrations are predicted to be. This corresponds to a confirmation type sampling design. The result is a design that will determine if the area has relatively high concentration values – hot spot confirmation.

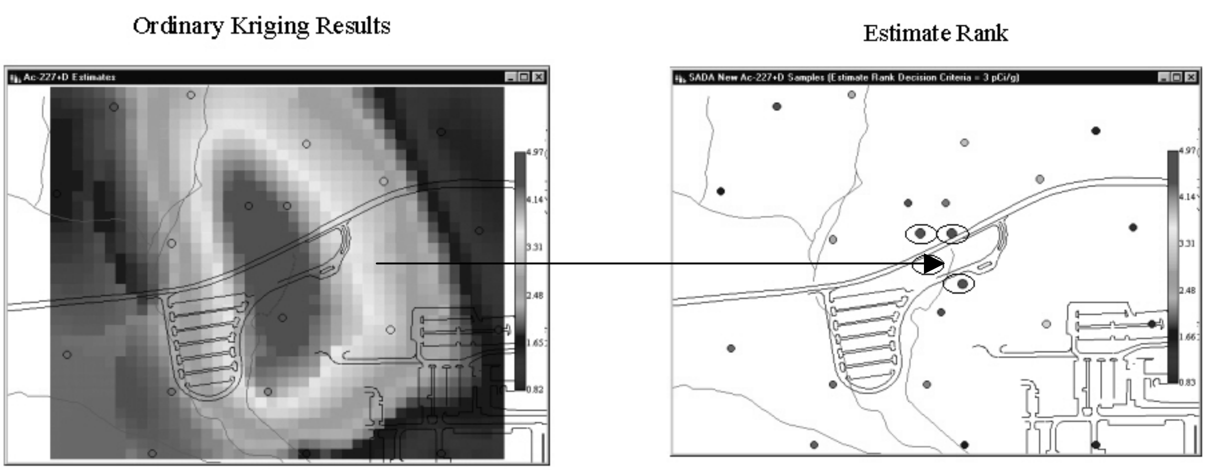


**Figure 11. Concentration Contours and estimate rank results.**

*Variance Rank*
This sampling strategy is based on the ordinary kriging method, where model variances are produced along side concentration estimates. These two quantities define a distribution of possible concentration values at each point. This sampling strategy will place new samples where the model variances are the highest and will result in a sampling design that reduces modeled variability.

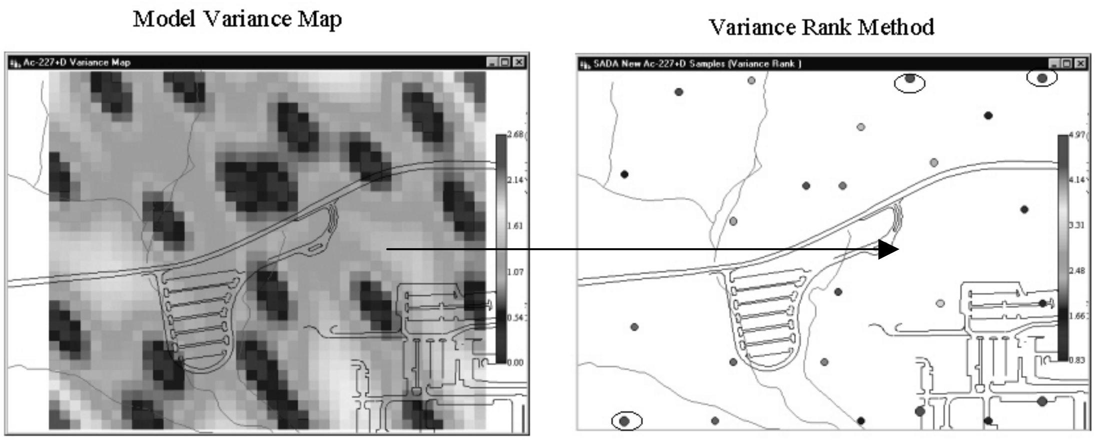


**Figure 12. Model variances and variance rank sample design.**

*Percentile Rank*
Geostatistical routines, such as ordinary and indicator kriging, will provide a distribution of possible concentration values at any unsampled point. This distribution describes the magnitude and variability in the modeled response to the sample data. In percentile rank, the goal is to identify those points with the potential to have extremely high value due to the span of the distribution rather than those points that have the highest predicted value (usually corresponds to the mean type value for geostatistics). This approach is useful to sample for potential hotspots. The following figure is based on the 90$^{th}$ percentile. Unfortunately, a graph of the 90$^{th}$ percentile map is not available.

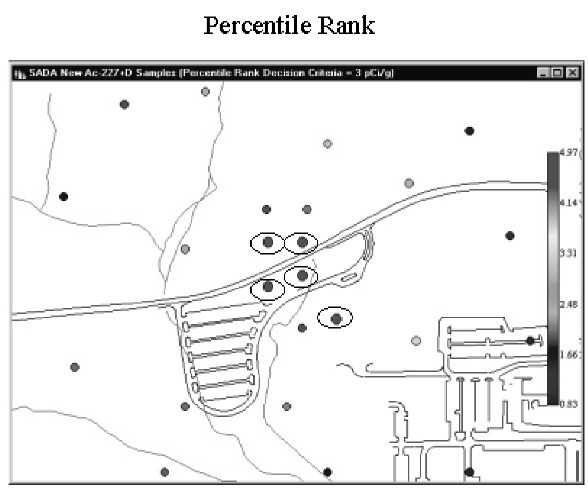


**Figure 13. Percentile rank results**

*Uncertainty Rank*
The uncertainty rank, like variance and percentile rank, assumes a geostatistical approach to contouring has been utilized. Uncertainty rank differs from the former methods in that it is directly connected to a decision criteria. In uncertainty rank, new samples are placed where the model is most uncertain about exceeding the specified criteria (i.e., Prob > Criteria ~ .50). This is primarily useful for delineating the boundaries of the area of concern.

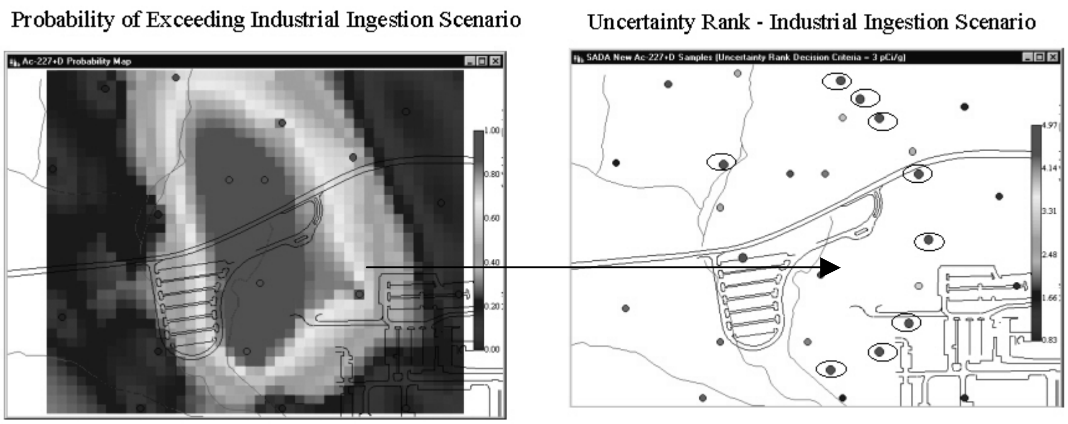


**Figure 14. Probability of exceeding risk limit and resulting uncertainty rank sample design.**

*Secondary Engineering Constraint*

For all strategies except adaptive fill, a secondary constraint is often required to create a viable sampling design. In each case, the mathematically optimal location is selected as the next new sample location. This location may be extremely close to another sample and therefore not practically optimal. As a result, a minimum distance constraint may be useful. In this secondary engineering constraint, new samples are forced to be separated from existing data as well as themselves by a specified distance. This results in sampling designs that optimize with respect to a design goal while spreading samples apart to also give better spatial coverage within the area of interest. A secondary constraint of 100 feet was used for all the examples in this section.

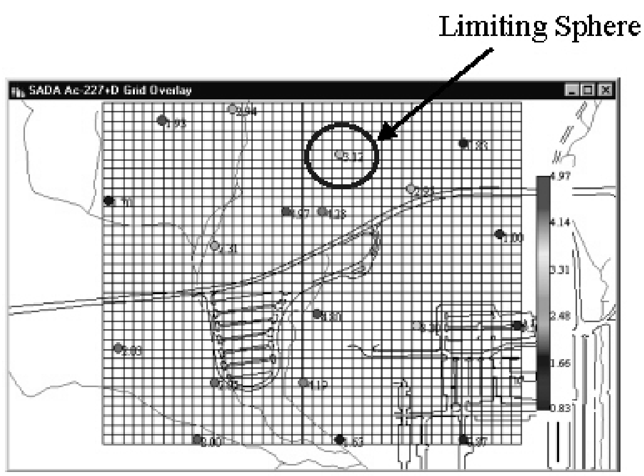


**Figure 15. Secondary distance constraint. The limiting sphere applies to all new and old samples.**

*When to Stop Sampling: A Value of Information/Economic approach*

A number of criteria for when to stop sampling are available. Most are statistically based and assume independence among the data or require the user to know something about the sampled object. A straight-forward "economic value of information" approach may provide another tool for determining when to stop sampling. This approach integrates the geospatial analysis, decision criteria, sampling design, and cost. Simply stated, when new samples are not producing new information, sampling may stop.

This approach is presented in this paper from the perspective of geospatial and decision analysis. The particulars of what is meant by "no new information" will vary widely within characterization studies.

In the following exercise, the concept of "value of information" is demonstrated with a simple geospatial analysis. The modeling results are shown for each round of sampling. As the number of samples increases, the model changes less.

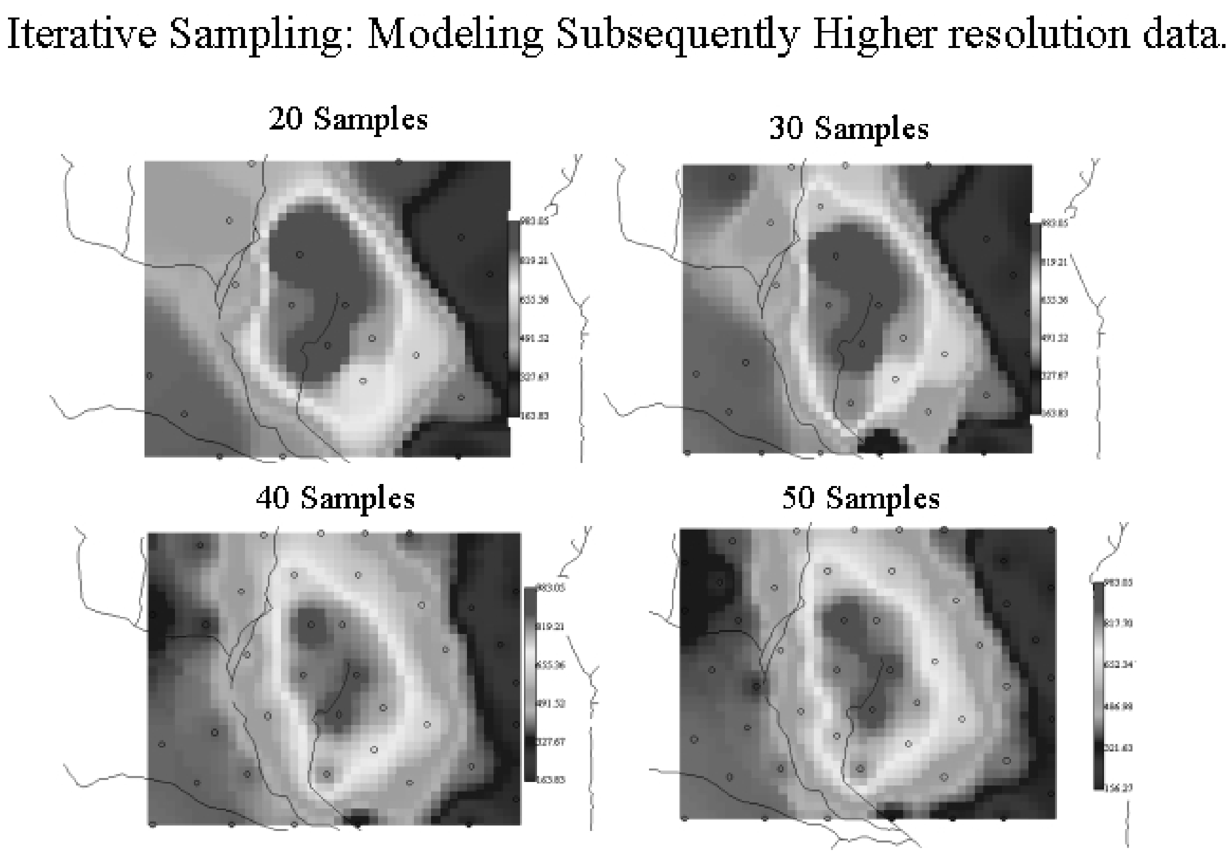


**Figure 16. Subsequent analysis result with each round of new samples.**

With each new sample, less new information is provided to the process. In fact, upon visual inspection, one can see that the difference between 40 and 50 samples if very little. The implications of using this approach are great for remedial design. For sampling designs that intend to refine the remedial process this approach is directly applicable.

**CONCLUSION**

Geospatial analyses can have an explicit and influential impact on environmental decision making processes. Delineating information within a spatial context aids in the definition of many decision processes and the quantification of their impact on cost and risk reduction. These impacts can result in enormous cost savings over traditional approaches. The methods presented in this paper represent the basic approaches in this area; more methods are being developed. All the described methods are available in the SADA software package, which can be freely downloaded at http://www.sis.utk.edu/cis/sada/.

# DECISION SUPPORT TOOLS: APPLICATIONS IN REMEDIATION TECHNOLOGY EVALUATION AND SELECTION

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**ABSTRACT**

Soil remediation is a difficult, time-consuming and expensive operation. A variety of mature and emerging soil remediation technologies is available and future trends in remediation will include continued competition among environmental service companies and technology developers, which will definitely result in further increase in the clean-up options. Consequently, the demand has enhanced developing decision support tools that could help the decision makers to select the most appropriate technology for the specific contaminated site, before the costly remedial actions are taken. Therefore, a Decision Aid for Remediation Technology Selection (DARTS) is currently being developed with the aim of closely working with human decision makers (site owners, local community representatives, environmentalists, regulators, etc.) to assess the available technologies and preliminarily select the preferred remedial options. The analysis for the identification of the best remedial options is based on technical, financial, environmental, and social criteria. These criteria are ranked by all involved parties to determine their relative importance for a particular project.

**Key words:** decision support tools, multicriteria optimization, soil remediation

## INTRODUCTION

Remediation of contaminated soils is a field of technology that has developed and grown recently. Development and use of remediation technologies has progressed and a large number of clean-up alternatives have evolved and improved over the past decade. In addition, the technology developers and environmental service companies have sprung up in the hope of secure a place for their process in the market. Therefore, there has been a remarkable decrease in unit cost for land treatment options. Remediation has become affordable, allowing owners of small- and medium-sized contaminated sites to undertake soil clean-up programs in a more cost–effective manner. However, both site owners and environmental managers confront the challenge of making decisions to select and deploy the most suitable soil remediation technologies to address a variety of problems and, in some cases, satisfy a number of conflicting criteria.

These choices are increasingly more complex because a greater variety of contamination problems are being defined and innovative technologies are becoming available every day as potential (sometimes cheaper and/or more effective) alternatives to existing technologies (*1-3*). Innovative remediation technologies, which lack a long history of full-scale applications, do not have, in some cases, the extensive documentation necessary to make them a standard choice in the engineering/scientific community. However, many innovative technologies have been successfully used at contaminated sites in the United States, Canada, and Europe despite incomplete verification of their overall performances. Some of the technologies were developed in response to hazardous waste problems and some have been adapted from other industrial uses. Only after a technology has been used at many different types of sites, and the results fully documented and assessed, it is commonly considered as a well-established technology.

Decision makers are also asked to integrate information about remedial options and are required to balance information about technology performance with limited budgetary resources and regulatory constraints. In addition, information about the concerns of stakeholders, as well as their meaningful involvement in the larger decision process, influences the ultimate technology selection and deployment decision. Therefore, all involved parties (environmentalist, policy makers, local community representatives, site owners, other stakeholders) need some tools to help them assembling and synthesizing information to respond to these challenges and conflicting issues.

Therefore, this problem has been chosen to develop DARTS in order to perform evaluation and comparison of technologies for environmental remediation. DARTS provides a set of criteria for evaluating technologies to address site-specific clean-up activities, and would accomplish the following tasks:

- To enable users to identify and systematically compare information about innovative and conventional technologies to meet remediation goals, highlighting their strengths and weaknesses
- To establish a structure of technology evaluation and selection process, which simplifies the decision-making and streamlines the variety of factors involved in the remediation process
- To define consistent, qualitative and quantitative indicators for key technical, environmental, economic, and legal criteria that influence selection and deployment of technologies
- To provide documented, reproducible evaluation which can be updated as needed information becomes available
- To provide flexible, multicriteria optimization approach allowing trade-offs among criteria on the basis of contaminant type and site-specific needs
- To enhance communications and help focus dialogue between local community, environmental managers and stakeholders, including regulators and policy makers
- To enable explanation and justification of the choice by offering evidence on the advantages and disadvantage of the possible choices in a concise and consistent way.
- To fasten development of feasibility study of the remedial options
- To provide site owners, environmental managers and other stakeholders with the opportunity to explore alternative options, etc.

Before a treatment technology can be selected for a contaminated site, detailed information about the site and contaminants characteristics must be collected. DARTS uses this information to determine which of the possible remedies will be capable of meeting the clean-up standards set by its users, respecting the previously mentioned constraints (technical, economical, legal, etc.). The following section will further clarify the role of DARTS in supporting remedial actions.

DARTS functionality

Remedial actions usually involve these main tasks:

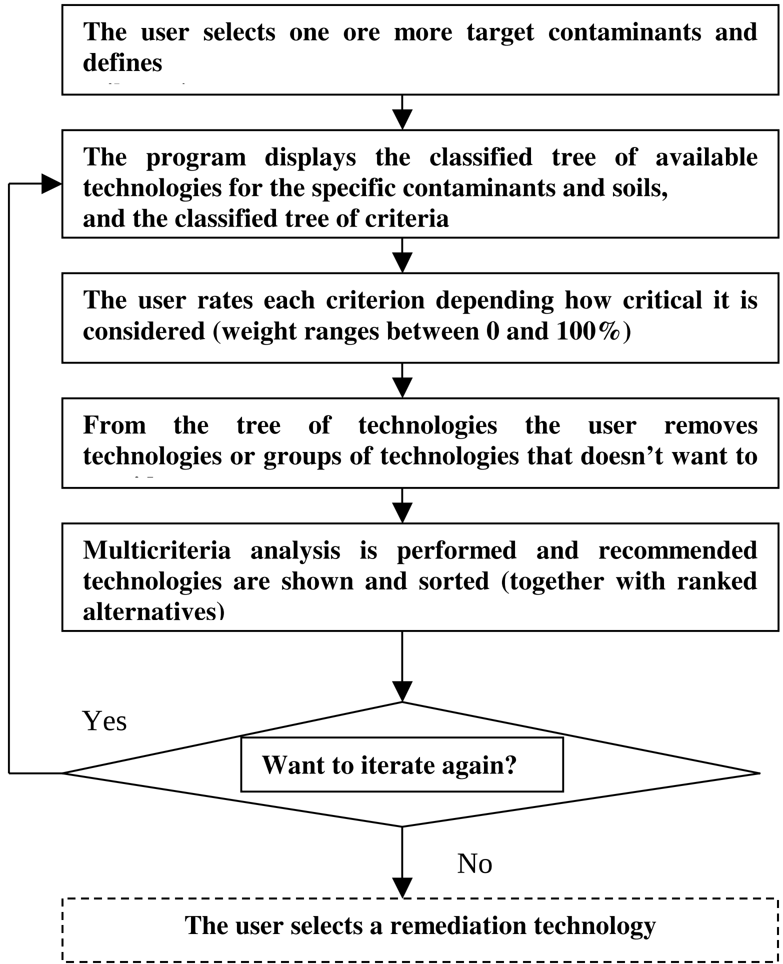
- *Site discovery*, preliminary assessment, and site inspection, conducted to quickly determine if there is a contamination problem.
- *Site assessment* that determines the type and extent of contamination
- *Evaluation of clean-up alternatives*, and selection of remediation technology, based on the type and extent of contamination, clean-up time required, physical, and geological site characteristics, available technologies, resource requirements, social acceptance, and compliance with federal and state laws, etc.
- *Site clean-up*, application of selected remediation technique, and
- *Site closure and compliance monitoring*, ensuring that the identified contamination problems have been adequately addressed

DARTS aims at providing a decision support for the evaluation of clean-up alternatives and selection of the best available technology for the site concerned, simultaneously taking into account a number of different technical, economic, social, legal and environmental criteria. Each criterion could be weighted by the panel of experts, environmental managers, technology providers, policy makers, local community representatives, to capture its relative importance in the overall balance.

There are many actors in the decision-making process, which have their own interests and perspectives. For instance, the person(s) responsible for contamination and the owner of the polluted plot of the land can be mainly interested in the financial issues, while the user of the plot and the direct environment, including nearby residents, are mainly interested in health and environmental issues. Another group is composed by representatives of public bodies. They should consider the overall interests, which includes socio-economic and environmental issues.

The aim of DARTS is working with all mentioned actors to perform a preliminary selection of the most efficient remediation technologies, by analyzing simultaneously some key criteria of available remedial techniques. These criteria can be ranked by all involved parties to determine their relative importance for a particular project.

Multicriteria analysis of all these factors determines whether a remediation strategy is a feasible, effective and efficient solution and whether it satisfies all criteria and constraints defined by the user. Depending on the context in which remediation technology assessment and selection are performed, the users can tailor decision strategy balancing out various effectiveness and efficiency parameters, other criteria and constraints. From the user’s point of view, a general algorithm for DARTS analysis is described in Figure 1.




*** Soil type option in current implementation**

An example of practical approach using DARTS is when applying a soil remediation decision tree (*4*) (Figure 2); in this case, the user is able to analyze and compare subgroups of technologies, or to compare technologies within the same subgroup. The technologies available in the current stage of DARTS are indicated in Figure 2. This approach also applies for groundwater remediation programs, which can be integrated in the remediation decision tree supported with DARTS.

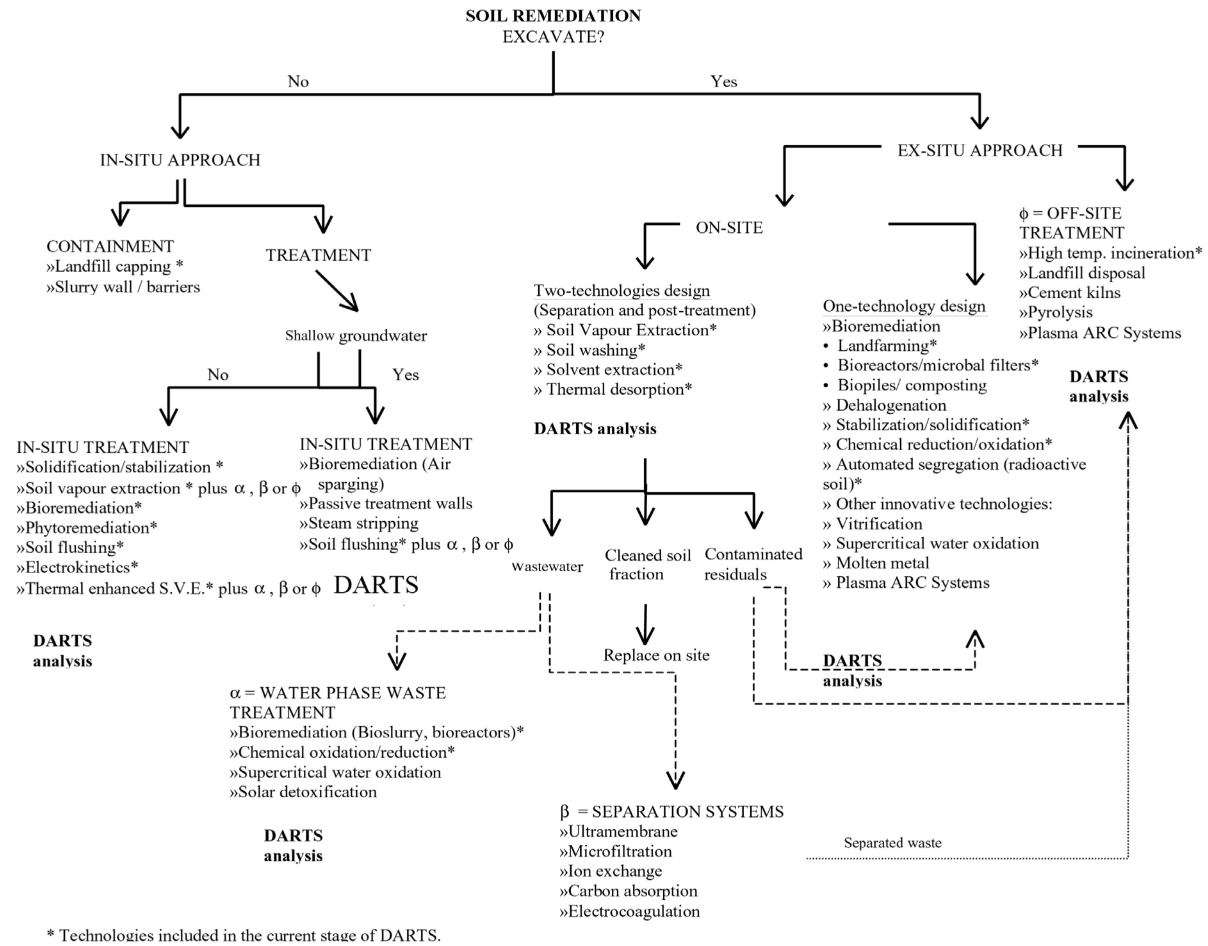



**Figure 2. Soil remediation decision tree supported with DARTS**.

## CRITERIA TO ASSESS AND SELECT REMEDIATION TECHNOLOGIES

DARTS' user selects a subset of technologies in which is interested, or uses a full set of technologies and ranked criteria (*6,7*); selects the criteria, preference functions (or use default functions chosen by the DARTS developers) and corresponding weighting factors, defines the contaminant (or a group of contaminants), soil type and then performs a multicriteria analysis.

The criteria included in the current stage of DARTS prototype are applicability, overall cost, minimum achievable concentration, clean-up time required, reliability and maintenance and public acceptability (that varies depending on the country and site location); two more criteria are currently being implemented: by-products/wastestreams post treatment required and decontaminated soil quality. A numerical rating of 1 (= better), 2 (= average) or 3 ( = worse) is given to each technology in each category (*6*). These categories are taken from the ratings reported in UN-ECE Compendiums of soil remediation technologies (*6,7*), and are mainly based on the US-EPA's evaluations. The categories are briefly explained below.

Overall cost. *Includes design, construction, operation and maintenance costs of the core process that defines each technology. It does not include site preparation or post-treatment costs. Excavation costs of $55/metric ton are assumed for ex situ technologies.*

Ratings: 1= Less than $110/metric ton;

2= $110 - $330/metric ton;

3= More than $330/metric ton

*Minimum achievable concentration*. Refers to the minimum pollutant concentration achievable by the technology.

Ratings: 1= Less than 5 mg/kg soil;

2= 5-50 mg/kg soil; and

3= More than 50 mg/kg soil

*Clean-up time required*. This refers to a "standard" site of .41 hectare and 3.04 m depth. The soil mass is 18,200 metric tons.

Ratings for ex situ techniques:

1= Less than 6 months;

2= 6 months -1 year; and

3= More than 1 year.

Ratings for in situ techniques:

1= Less than 1 year;

2= 1-3 years; and

3= More than 3 years.

*Reliability and maintenance*. Refers to the level of complexity of the system or technology, and how easy it is to maintain.

Ratings: 1= High reliability and low maintenance;

2= Average reliability and maintenance; and

3= Low reliability and high maintenance

*Public Acceptability*
Degree to which the technology is acceptable to the public. This category can, of course, vary widely depending on the country and the level of community involvement.

Ratings: 1= Minimal opposition from the community is likely;

2= Public involvement usually occurs, but the technology is generally accepted;

3= Serious public involvement is likely and the outcome is uncertain.

Other ratable criteria that will be included in the system prototype are: data needs/characterization (refers to the extent of pre-remediation investigations) and safety requirements (refers to the measures required to ensure safety of workers, public and environment).

**MULTICRITERIA ANALYSIS ALGORITHM**

A multicriteria analysis performed by DARTS is the process during which the relative merits of the remediation alternatives are compared to each other and the most appropriate is selected from among them for site clean-up implementation.

There are a number of fundamental problems when there are multiple objectives. For instance, consider the case where there are a number of decision makers, each with a preference ordering over a number of alternatives. The goal is to choose the ``fair'' alternative that aggregates the preferences of the decision makers. This is an example of multiple criteria decision making (each decision-maker represents one criterion), and those objectives need to balance in a fair way. The situation is even more complicated when there are also multiple and even conflicting criteria like in the DARTS (where for instance, minimizing cost and clean-up time could be conflicting requirements). The decision-maker is asked to specify goals and relative weightings for the different criteria. Relative weightings are used to find most preferred solutions. The weighting can be changed to assess sensitivity of solution or to reflect different opinions.

The explicit consideration of multiple, even conflicting objectives in a decision model has made the area of multiple criteria decision-making (MCDM) very popular among researchers during the last two decades. It is quite conceivable that certain modifications in the existing MCDM procedures provide the long awaited bridge between the important fields of Operations Research and Decision Support Systems. In order to support the decision maker that must solve multicriteria problems, three kinds of methods were essentially considered - aggregation methods using utility functions, interactive methods and outranking methods. In our work, we adopted the last ones, actually a special outranking method, based on extensions of the notion of criterion (*5*) (PROMETHEE I, providing a partial preorder, and PROMETHEE II, providing a total preorder on the set of possible decisions).

These extended criteria can be easily defined by the decision maker, because they represent the natural notion of intensity of preference, and the parameters to be fixed (maximum 2) have a real world meaning. The extension is based on the introduction of a preference function, giving the preference of the decision maker for an action *a* with regard to *b*. This function is defined separately for each criterion, where its value is between 0 and 1 (meaning a range between 0 and 100%), within the same defined criterion. The smaller the function, the greater the indifference of the decision maker; the closer to one, the greater his preference. In case of strict preference, the preference function is 1. Numerous practical applications of the PROMETHEE method have shown that it is very easily accepted and understood by the practitioners, being the easiest approach for solving a multicriteria problem by considering simultaneously extended criteria and outranking relations.

A preference function, $P_h(a, b)$, is usually presented by a function $p(x)$:

$$p(x): x \rightarrow [0, 1] \text{ and } x = f(a) - f(b),$$

where $f(a)$ and $f(b)$ represent the values of a particular criterion, *h*, for actions *a* and *b* respectively.

Using a preference index, $\pi(a, b)$, we can determine the preference for *a* with regard to *b* over all criteria:

$$\pi(a, b) = \frac{1}{\sum_{h=1}^{k} W_h} \sum_{h=1}^{k} W_h P_h(a, b)$$

where *k* represents the number of criteria, $W_h$ is a weight for the criterion *h*, and $P_h(a, b)$ is the preference function for the criterion *h*.

A *valued outranking graph* consists of nodes represented by actions and arcs, where each arc $(a, b)$ has a value $\pi(a, b)$. When obtained, the *valued outranking graph* offers a decision-maker means for determining a partial preorder (PROMETHEE I), or a total preorder (PROMETHEE II).

In order to rank the actions by a partial preorder, we must evaluate the outgoing flow:

$$\phi^+(a) = \sum_{x \in K} \pi(a,\ x),$$

where $K$ is the set of all actions, and the incoming flow:

$$\phi^-(a) = \sum_{x \in K} \pi(x,\ a).$$

The outgoing flow $\phi^+(a)$ describes the degree to which $a$ dominates the other actions in K, while the incoming flow $\phi^-(a)$ represents the degree to which $a$ is dominated. Using the outgoing and incoming flows, the two total preorders ($P^+$, $I^+$), and ($P^-$, $I^-$) can be defined, such that:

$$a\ P^+\ b \quad \text{if} \quad \phi^+(a) > \phi^+(b),$$

$$a\ P^-\ b \quad \text{if} \quad \phi^-(a) > \phi^-(b);$$

$$a\ I^+\ b \quad \text{if} \quad \phi^+(a) = \phi^+(b),$$

$$a\ I^-\ b \quad \text{if} \quad \phi^-(a) = \phi^-(b).$$

Then the partial preorder ($P^{(1)}$, $I^{(1)}$, $R$) can be determined by considering their intersections:

$$\begin{cases} a \text{ outranks } b\ (a\ P^{(1)}\ b) & \text{if } \begin{cases} a\ P^+ b \text{ and } a\ P^-\ b, \\ a\ P^+ b \text{ and } a\ I^-\ b, \\ a\ I^+ b \text{ and } a\ P^-\ b, \end{cases} \\ a \text{ is indifferent to } b\ (a\ I^{(1)}\ b) & \text{if} \quad a\ I^+ b \text{ and } a\ I^-\ b, \\ a \text{ and } b \text{ are incomparable } (a\ R\ b) & \text{otherwise.} \end{cases}$$

The net-flow: $\phi(a) = \phi^+(a) - \phi^-(a)$

is used to rank the alternatives by a total preorder ($P^{(2)}$, $I^{(2)}$):

$$\begin{cases} a \text{ outranks } b\ (a\ P^{(2)}\ b) & \text{if} \quad \phi(a) > \phi(b), \\ a \text{ is indifferent to } b\ (a\ I^{(2)}\ b) & \text{if} \quad \phi(a) = \phi(b). \end{cases}$$

**DARTS EXPERIMENTAL PROTOTYPE**

A laboratory prototype of DARTS has been developed as JAVA application, using Symantec Visual Café dbDE development environment.

The DARTS presents its users with a variety of configuration and input parameters from which to choose. Several are mandatory (such as identifying technologies to be evaluated), but there are many that the user can choose to leave blank or use the supplied default values. This way, the user decides how to tailor the analysis to satisfy specific needs.

Prototype configuration and data entry process involves several tasks:

- Entering available technologies and their descriptions
- Entering criteria to be considered simultaneously
- Setting values of chosen criteria and selecting the type of preference function for each criterion

The application's main window (Figure 3) consists of the current state of configuration, and a few dialogs for data entry purposes. It is connected to the database that contains previously entered information on available technologies and selection criteria; database should be registered by the user and/or software administrator. An application window consists of the following sections:

- *Technologies* tree structure
- Buttons for manipulating nodes of the *technologies* tree
- *Criteria* tree structure
- Buttons for manipulating nodes of the *criteria* tree
- Button for setting values of the selected criteria
- Button for starting multicriteria decision making process
- Button for selecting contaminants for multicriteria decision making process

A dialogue box requesting the user to select the technologies to be simultaneously evaluated and compared with one another is shown in Figure 3.

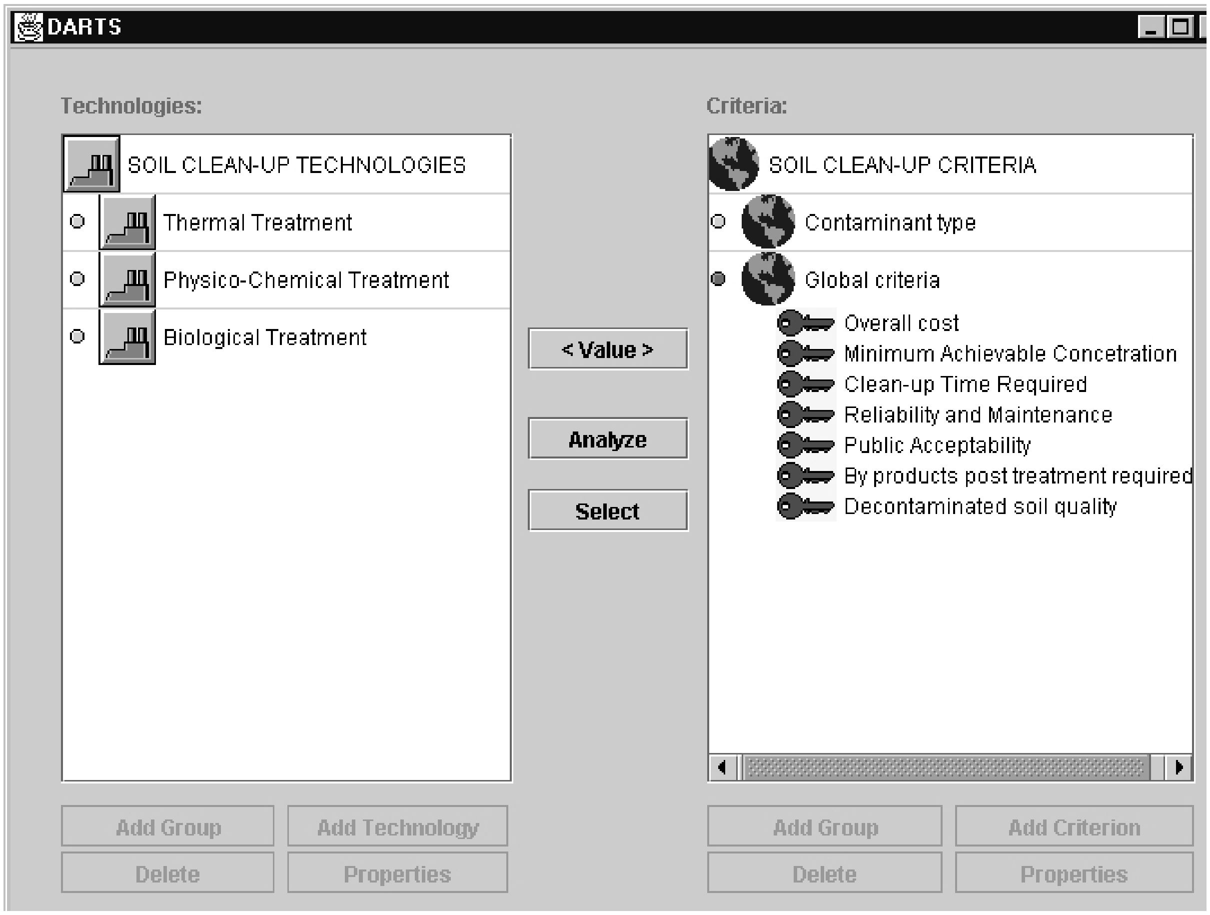



**Figure 3. Main application window**

A dialogue box *Technology Properties* (Figure 4) is used for entering and updating information on particular technology. It consists from a few text fields and standard OK and Cancel buttons. Main fields are for technology identification code, name and description. Three other text fields are disabled, and they are used for presentation of multicriteria analysis results. Radio buttons *On* and *Off* are used for including/excluding selected technology in multicriteria analysis.

A dialogue box *Criterion Properties* (Figure 5) is used for entering and updating attributes of particular criterion. It consists of several text fields, four radio buttons, and standard OK and Cancel buttons. Main fields are for criterion identification code, name, weighting factor, function ID, i.e., he identification code of the selected preference function for the criterion, and its parameters. Radio buttons *On* and *Off* are used for including/excluding selected criterion in multicriteria analysis. *Min* and *Max* radio buttons show whether selected criterion is maximized or minimized.

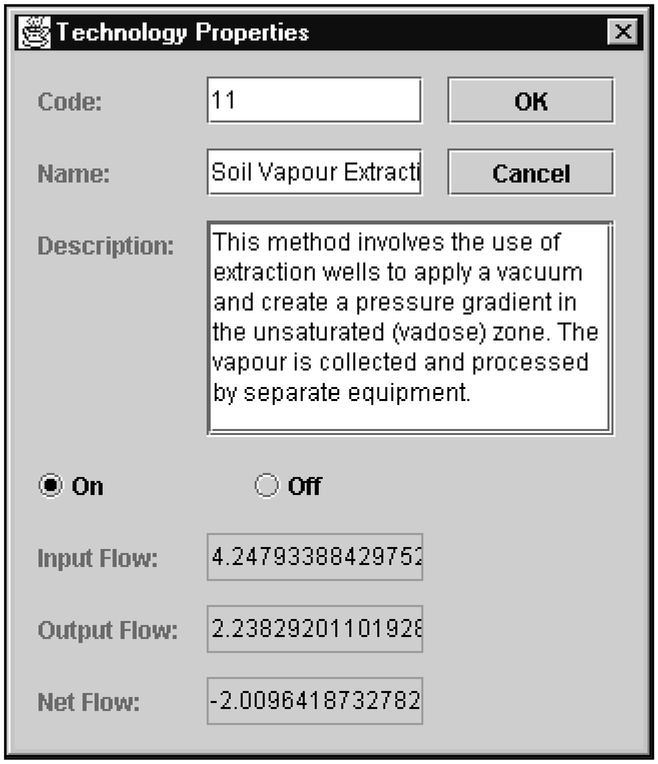



**Figure 4. Technology properties dialogue box.**

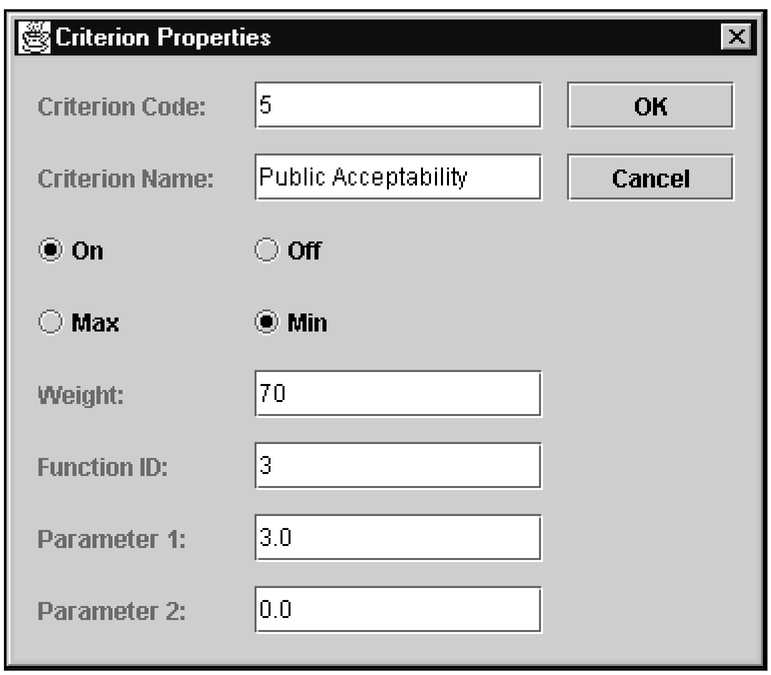



**Figure 5. Criterion properties dialogue box.**

A dialogue box *Criterion-Technology Properties* (Figure 6) is used for entering and updating a value of the specific criterion for selected technology.

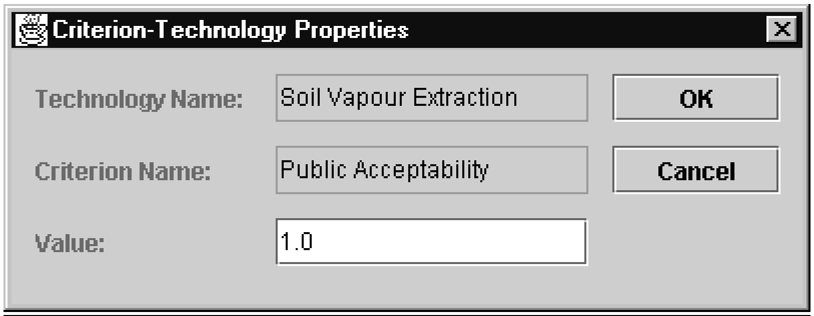



**Figure 6. Criterion-Technology properties dialog box.**

A window *Technology Criteria Overview* (Figure 7) is used to overview the values of all selected criteria for particular technology.

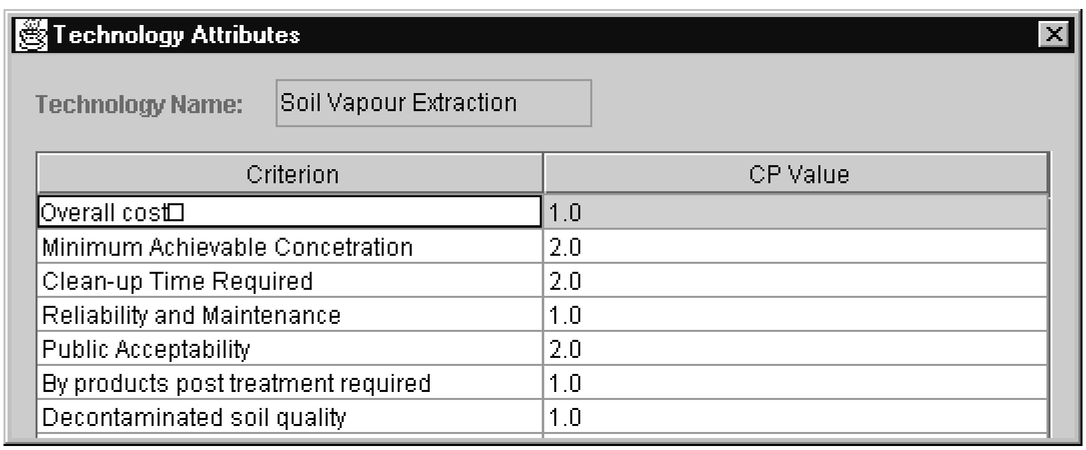
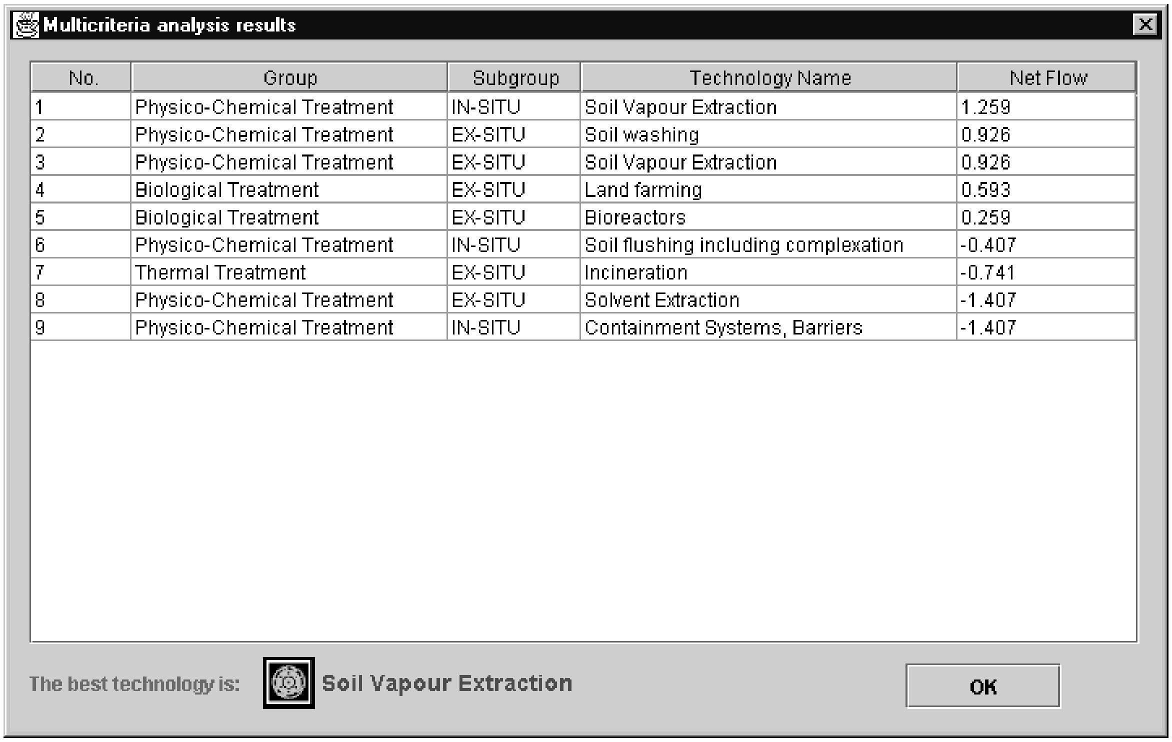



**Figure 7. Complete Technology criteria overview**

A window *Multicriteria analysis results* (Figure 8) is used for the presentation of the results of multicriteria analysis process. The best technology (with maximum net flow) is emphasized using red color. Here, the decision has been made upon the arbitrary choice of input parameters, so the results must not be taken seriously.




| No. | Group | Subgroup | Technology Name | Net Flow |
|---|---|---|---|---|
| 1 | Physico-Chemical Treatment | IN-SITU | Soil Vapour Extraction | 1.259 |
| 2 | Physico-Chemical Treatment | EX-SITU | Soil washing | 0.926 |
| 3 | Physico-Chemical Treatment | EX-SITU | Soil Vapour Extraction | 0.926 |
| 4 | Biological Treatment | EX-SITU | Land farming | 0.593 |
| 5 | Biological Treatment | EX-SITU | Bioreactors | 0.259 |
| 6 | Physico-Chemical Treatment | IN-SITU | Soil flushing including complexation | -0.407 |
| 7 | Thermal Treatment | EX-SITU | Incineration | -0.741 |
| 8 | Physico-Chemical Treatment | EX-SITU | Solvent Extraction | -1.407 |
| 9 | Physico-Chemical Treatment | IN-SITU | Containment Systems, Barriers | -1.407 |

**Figure 8. Multi-Criteria analysis results**

Please note that the above results are obtained for arbitrary set of contaminants, selection criteria and their values and preference functions. Soil Vapor Extraction Technology has been recommended as the best choice for this random selection of input parameters. We deliberately avoided presentation of the real world, interactive decision-making session with DARTS.

## DARTS TESTING

Several tests have been made in order to verify the accuracy of DARTS results against reported real cases. Some criteria considered by Brownfields Technology Support Center (*8*) for selecting and recommending remediation technologies for the Union Pacific Railroad Site (UPRS), Clinton, Iowa, are presented in Table1.

In the first step, the conditions measured in the study case were translated to parameters in DARTS, which are presented in Table 2. In order to make the DARTS analysis results comparable to those of Brownfields, the analysis was separately performed for each group of contaminants (VOCs and heavy metals).

**Table 1. Parameters obtained from Environmental Assessments performed on UPR Site, Clinton, Iowa.**

| **Criteria / Parameter** | **Description** | |
|---|---|---|
| Applicability | VOCs and Petroleum hydrocarbons in soil and groundwater | Arsenic in soil<br>Arsenic and lead in groundwater |
| Risk-based clean-up level * | 22 ppm (benzene in soil)<br>0.36 ppb (benzene in gw.) | 3.8 ppm (arsenic in soil)<br>0.045 ppm (arsenic in gw)<br>50 ppm (lead in gw) |
| Clean-up time required | < 1 year | < 1 year |
| Cleaned soil availability | To be used as a light industrial and/or commercial retail area | |

**Table 2. Criteria translated to parameters in DARTS.**

| **Criteria / Parameter** | **Description**<br>**Weight ( % )** | |
|---|---|---|
| Applicability | VOCs / Hydrocarbons<br>100% | Heavy metals<br>100% |
| Minimum achievable concentration | 5 – 50 mg/kg (benzene)+<br>>50 mg/kg (other hydrocarbons)<br>30 – 50% | < 5 mg/kg (arsenic)<br>100% |
| Clean-up time required | < 1 year<br>50% | < 1 year<br>50% |

+Benzene concentrations detected during Environmental Assessments were always below 22 ppm.

**Table 3. Comparison of recommendations made by Brownfields and those obtained with DARTS.**

| *Brownfields recommendation* | *DARTS Multicriteria Analysis results** | *DARTS ranked list* |
|---|---|---|
| | ***VOCs / Hydrocarbons*** | |
| Air sparging | Thermal desorption | 1.302 |
| Bioremediation (ex-situ) | Chemical treatment | 1.036 |
| Bioslurry (ex-situ) † | Thermally enhanced soil vapor extraction | 1.036 |
| Bioremediation gw (in-situ) | Soil Vapor Extraction/ Air sparging (in-situ) | 0.770 |
| Bioventing † | Bioreactors | 0.770 |
| Chemical treatment | Soil Vapor Extraction (ex-situ) | 0.770 |
| Dual phase extraction † | Solvent extraction | 0.504 |
| Soil flushing | Land farming | 0.504 |
| Soil vapor extraction | Bioremediation (in-situ) | 0.504 |
| Thermal desorption | Soil flushing | 0.238 |
| | ***Heavy metals*** | |
| Chemical treatment | Chemical treatment | 1.232 |
| Phytoremediation | Phytoremediation | 0.700 |
| Soil flushing | Solidification/stabilization (ex or in-situ) | 0.700 |
| Solidification/stabilization | Solvent extraction | 0.700 |
| Solvent extraction | Containment systems / Barriers | 0.168 |
| | Soil flushing | 0.168 |

* “Overall cost” not included as criteria. † Technologies not available in current DARTS prototype.

DARTS results are presented and ranked in Table 3, and are compared against recommendations made by Brownfields. Most of the technologies proposed by DARTS are included in Brownfields recommendations, only some variations of Bioremediation (Landfarming and Bioreactors) do not match since these technologies are grouped in DARTS as Bioremediation. Soil flushing is ranked on the last place, because its low ability to clean until acceptable levels which DARTS considers as more than 50 mg/kg soil. UPRS case requires between 5-50 mg/kg for benzene and less than 5 mg/kg.

Some biological remediation technologies (bioremediation *in-situ* and landfarming) are also classified on the last places because of their high times required to complete the clean-up (usually more than 1 year). In the UPRS case, it was proposed a restriction of time: less than one year. If the overall cost were considered, the bioremediation technologies would increase the ranked level because of its lower cost compared to other thermal or physical-chemical technologies.

Coming to the end, the selection of the remediation technology is a matter of balancing out environmental achievements against reasonable cost. Different technologies have different performance, and this holds for technical and financial aspects as well as for environmental aspects. The aim of DARTS is to help integrating all these aspects and make a comparative analysis of the best available technologies, taking into account site-specific requirements, and various criteria set by environmental managers, policy makers, site owners and other stakeholders.

Internet accessible version of DARTS is currently under construction. The client-server architecture adopted for Internet version, assumes that all the analysis and database administration is done at the server side, while a light client (i.e., a distant user) needs only a standard Web browser and proper authorization to access and use the DARTS.

## ACKNOWLEDGMENTS

The authors wish to express their gratitude to Vladimir Simeunovic for his precious contribution during the development of the experimental prototype of the software. The authors also thank Branislav Opacic for his support during the project.

## SUPPORT INFORMATION AVAILABLE

Information about conventional and innovative remediation technologies is available free of charge via the Internet at http://www.environment.gov.au/epg/swm/swtt/contents.html, http://www.frtr.gov and http://www.epareachit.com. The Compendium of soil clean-up technologies and soil remediation companies, edited by ICS-UNIDO and UNECE, offers three sections: soil clean-up technologies and criteria to assess the options, list of web sites describing remediation technologies and a worldwide directory of companies dealing with soil remediation.

Additional information about Multicriteria Decision Making (MCDM) Methodologies can be found in:

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# COMMON FACTORS IN DECISION MAKING AND THEIR IMPLICATIONS FOR DECISION SUPPORT FOR CONTAMINATED LAND IN A MULTIOBJECTIVE SETTING

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## ABSTRACT

Arriving at the best soil remediation alternative involves a decision process. Tools can support some of the routines within the decision process. Support, however, is not the same as taking a decision. The actual deciding is not provided by a tool, but remains the shared responsibility of the stakeholders. Decision processes can be seen as goal-oriented systems. The informationless paradigm – giving it a try - is the least powerful in achieving a high performance. The feedback paradigm performs better since it allows learning from experience. The feedforward paradigm allows anticipation. The full-information paradigm combines the benefits of both the feedback and the feedforward paradigm. Although we like to focus on the decision process our attention should be stretched to the resulting remedial actions and feedbacks and feedforwards should consequently enable those involved to anticipate and learn from the results of the actions. Different stakeholders often have different objectives and, thus, their preference for remedial alternatives may differ. Nevertheless multiattribute models are useful tools when trying to make a decision. Three decision support tools are discussed in terms of their role in the decision process, the way they allow for feedback and feedforward, and, the way they support decision making in a multiobjective setting.

## ONCE UPON A TIME …

Quite a few years ago I had to visit one of our offices in Germany. When I arrived from the Netherlands I found a rather depressed team. They just received some very negative comments on what they considered as an almost perfect report on a chlorinated hydrocarbon problem. Still unaware of the nature of the comments I started reading the report, and after a few hours I had to admit that it was an excellent report. It gave very complete and detailed insight in the situation, and I could not detect the flaws. I did some more talking with the guys involved, to discover what could be wrong, but it was not very helpful. After that I called the problem owner, made an instant appointment, took my bike, and cycled across the Rhine-bridge to pay him a visit. The problem owner – an experienced manager – told me that it was the first time that he was confronted with contaminated land issues. After a half-hour the problem was a lot clearer: the problem owner expected a report listing the complete consequences for his company, and all he got was an expensive report that stated that his site was contaminated! It took me another hour to fill in the communication gap completely. At the end of our session we made another appointment to discuss the remedial options, and I managed to convince him to involve the (city) authorities. Back at the office I explained what went wrong, and they were happy that things had been solved. Since I promised the problem owner to invite the authorities, the next thing I did was making a phone-call to the city hall. Very soon after I got the responsible guy on the telephone I knew that I was talking to a fundamentalist: “Multifunctionality! No compromises to the environment!” I started hating myself to involve the authorities as early as I did. We had one week to prepare the meeting. My team members worked out a number of alternatives: the geohydrologist had worked out a geohydrological containment option, our civil engineer had worked out something that would put ‘his’ Caterpillars and Komatsus at work, and our chemical engineer came up with an innovative in situ alternative in which phenol was proposed as a co-substrate for chloroethene degrading bacteria. We just had success with such an alternative in the Netherlands, and so I asked our chemical engineer to prepare for the meeting.

Finally, we all met to discuss the options. Everybody had spelled every letter of the proposed alternatives. Within three minutes the situation was clear: the problem owner made his choice for the containment, the cheapest solution; the authorities made their choice for the excavation, the safest but most expensive solution; and our chemical engineer expressed his preferences for the smart and elegant in situ alternative. The authorities made it perfectly clear that infiltration of things like phenol were forbidden. By law! I tried to start a discussion, but after half an hour everybody had disappeared in his own trench. Within the hour I had managed to succeed in three things: the problem owner – our client – was confronted with the highest remediation costs possible, the local authorities would never accept any Tauw alternative for the next decade, and my colleagues would never take any communication lesson from me again. This time depression was mine …

Three weeks later we had the next meeting. By that time I had spend many hours doing my homework, and lost my day and night rhythm completely. For each of the alternatives I had figured out the effects from every possible perspective. My reasoning, which was based on a newly developed method for the comparison of remedial alternatives, pointed out that the cheapest alternative – the geohydrological containment – was save, required a lot of energy and renewable sources, but solved little. Moreover, the alternative could give problems in case of a future take-over of the site. The safest option – excavation – was very expensive and required a huge amount of energy and renewable resources. In terms of environmental merits the alternative had a negative score. The in situ alternative was not the cheapest, but still a lot closer to the price of the containment, than to that of the excavation. It would not yield quite the same reduction of pollutant concentration as the excavation, but it would be very close to that. In terms of environmental merit it was outperforming the other alternatives completely: low energy use, the use of renewable resources was negligible, and so on. Last but not least: with the predicted results, the owner could sell the site without any problem, and phenol as co-substrate could be replaced by something more acceptable. To make a long story short: we were asked to work out the in situ alternative; it was implemented; it took one year longer than predicted; and after four years we all celebrated the completion of the project, and we all agreed to publish our bloopers.

The story above never happened to me as a whole. It was not in Germany. I never did meet such ugly caricatures, and I was most certainly not always the hero I liked to be! Yet, I lived through most of the scenes that I have combined above: they are scenes of the profession collected all over the place, and I feel that the whole story could have happened to me. Fortunately, caricatures such as described do not exist, and they never met each other, but some people do at least remind me of these caricatures, and they could have met.

There are patterns in decision making, in the way we anticipate, in the way we learn, and in the way people interact when defending their own interest. Such patterns are described within alien sciences such as systems science and management. Having the made-up story at hand makes it easier for me to explain, and that is exactly why I started as a storyteller.

## DECISION MAKING PROCESSES

Arriving at the best soil remediation technique involves a decision process. A general model for decision processes (Figure 1) is given in Mintzberg et al. (1976). The seven central routines in the figure can be linked to the three main phases of decision-making: problem identification, development of problem solving alternatives and selection of the best alternative. The identification phase consists of the central routines: *recognition*, in which the problem is recognised and evokes decisional activity and *diagnosis*, in which the decision makers seek to comprehend the evoking stimuli and determine the cause-effect relations for the decision situation. In our made-up story the problem owner recognised that he was having a problem, and asked a number of experts to work it out. The experts mistook this request for a diagnostic one. They used all their skills and tools such as geographical information systems, geohydrological models, laboratory experiments to provide the initially unwanted diagnosis. The development phase contains a *search* routine to find ready-made solutions and a *design* routine to develop tailor-made solutions. This was what the problem owner expected, but did not get at first. The selection phase contains a *screen* routine to reduce the number

of generated ready-made solutions, an *evaluation/choice* routine, which operates in three different modes - judgment, bargaining and analysis - and an *authorisation* routine to obtain approval. This is what happened after the first disastrous meeting. We used an analytical tool to compare the different remedial alternatives, and bargaining and personal expert judgment did the rest. These phases and routines can also easily be identified in most guidelines for contaminated soil (Gotoh and Udoguchi, 1993; Dreschmann, 1992; Eikelboom and Von Meijenfeldt, 1985).
Interrupts – act so as to prevent from proceeding continuously - may occur in the process, originating from the decision environment, and can delay, accelerate, stop or restart the decision process. Interrupts are caused by disagreement on the need to make a strategic decision. Internal and external interrupts are common in soil remediation and are related to the nature of the strategic decision. In our made-up project we faced an internal interrupt when the negative comments of the problem owner could not be processed by our experts. We faced an external interrupt when the stakeholders could not agree on a solution, and consequently could not make a decision. New option interrupts occurring when the decision scope is suddenly broadened by technological development or changing policy are less common, but may occur in cases of considerable timelag between authorisation and the final realisation of a project.

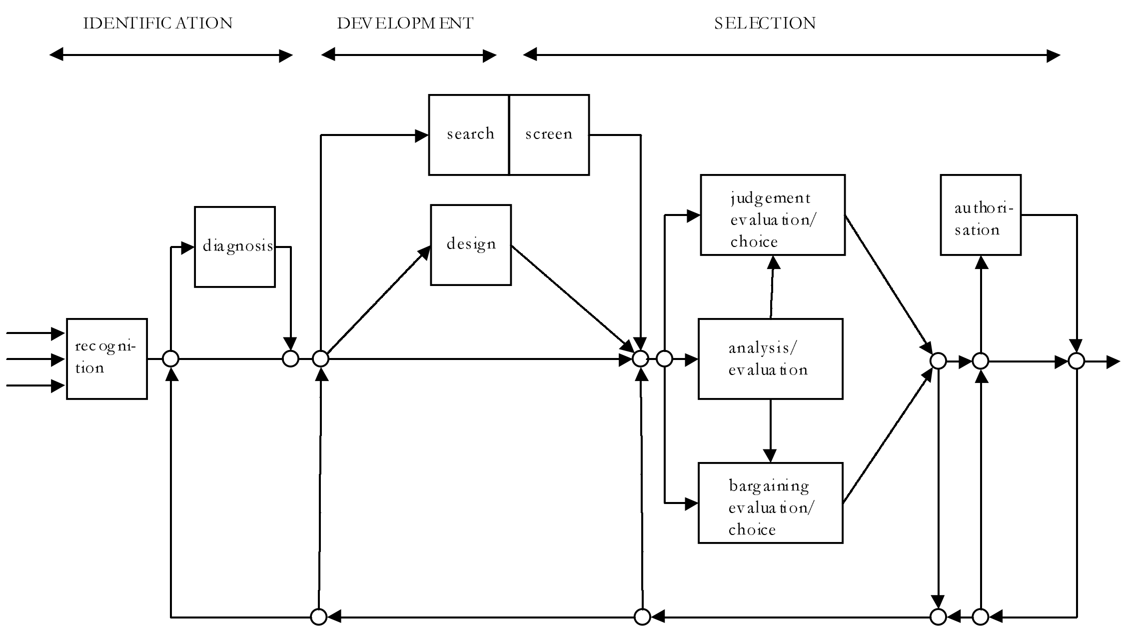


**Figure 1. A general model for decision processes (Mintzberg et al., 1976)**

Seven types of decision processes according the path taken through the Mintzberg's model are identified (Mintzberg et al., 1976; Nutt, 1984; Janssen, 1992). Only two of these will be referred to in this paper:

1. Modified search decision processes consisting of finding and modifying ready-made solutions.
2. Dynamic design decision processes, involving complex search and design cycles. These are the most complex decision processes.

For most remediation problems ready-made solutions do not exist. Therefore, the search and screen routines are always followed by a design routine in which ready-made in situ **concepts** are modified into **solutions**. Thus, selection of a remedial technology then should be considered as a modified search decision process, characterised by a development routine in which in situ concepts are modified into tailor-made solutions.

In some cases the development routine involves complex search and design cycles and encounters multiple interrupts. This corresponds to a so-called dynamic design decision process.

Tools can support some of the routines within the decision process. This kind of support is defined by Bardos et al. (2000) as: *the assistance for, and substantiation and corroboration of, an act or result of deciding; typically this deciding will be a determination of optimal or best approach*. More important than the definition is remark that decision support is not the same as taking a decision. The actual deciding remains the shared responsibility of those with a legitimate stake in the outcome of the decision, i.e., the stakeholders (Bardos et al., 2000).

## 1. INFORMATION PARADIGMS

Decision processes can be seen as goal-oriented systems (Klir, 1991). The most primitive paradigms of goal-oriented systems are usually conceived as structure systems with two elements. One of the elements is a system in terms of which the goal is defined. It is usually called a **goal-implementing element A**. You could call it the planned action. The other element, which is called the **goal-seeking element B**, generates states of a goal-seeking variable. It is equal to the actual experience. By using experience as an additional input to the goal-implementing element, its performance with respect to the goal increases. Block diagrams of four paradigms are displayed in Figure 2.

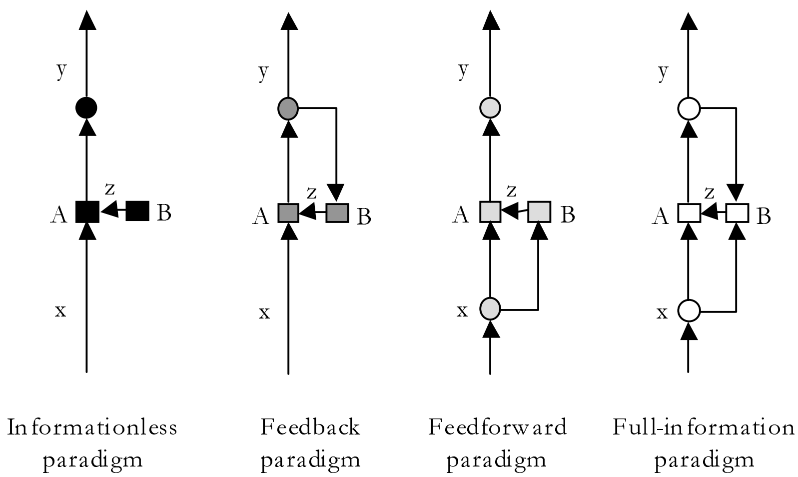


**Figure 2. Four information paradigms**

The **informationless paradigm** – act and hope for the best – is the least powerful in achieving a high performance. An example: people trying to sell standard solutions are often working this way. Whatever the situation is: they do not want to know about the specific situation, because they cannot anticipate and change the solutions they sell. And, as long as they cannot change the product, the performance of their solution is of no importance to them.

The **feedback paradigm** is less restrictive since it allows utilising information about the output variable. In plain English: it allows you to learn. Methods based on this paradigm are well developed. In the made-up story the experience from another project was used to develop the 'winning' alternative. Thus, the paradigm allows to learn and react, but does not provide for anticipation.

The **feedforward paradigm** provides the possibility to anticipate future events. In our made-up story we should have anticipated the reaction of the stakeholders involved.

However, both feedback and feedforward paradigms are inferior to the **full-information paradigm**. The full-information paradigm is the combination of the feedback and the feedforward paradigm.

Note: anticipation as well as learning can be applied to the reaction of stakeholders, as well as to physical phenomena such as the reaction of physical the contaminated soil to remedial actions. Watzlawick et al.

(1967) – a classical work for psychologist – give some fine examples of patterns/models related to human interaction.

If A is a good and deterministic model of the corresponding real phenomenon, then the feedforward mechanism may give better results than the feedback mechanism. If A is not a good model, then the feedback mechanism may lead to a higher performance (Klir, 1991). Thus, the feedback and the feedforward paradigms are not comparable and their performance depends on the circumstances.

So much for systems science, let us talk business again. Within the development phase of decision process we can try – for instance by involving the stakeholders - to anticipate to what might happen in the selection phase. Moreover, in an adaptive decision process such as the modified search or the dynamic design decision process each iteration allows including the ‘lessons learned’ from the selection phase. Thus, the decision process allows for the full-information paradigm. Although this is a promising start, we should not be satisfied. Our target – or goal-seeking element - is not the decision process, but the effect and the efficiency of the resulting action. After all in our made-up project we would not have been satisfied by an authorised failure! This implies that the decision process is only a part of the goal-oriented system. For full optimisation the system should stretch out to the resulting actions and feedbacks and feedforwards should consequently enable those involved to anticipate and react to the results of the remedial actions. This requires remedial designs that can be operated adaptively. If we do not provide this type of adaptive designs, then we cannot change the outcomes of our action, and the only option is to use the experience for some future project.

## 2. THE MULTIOBJECTIVE SETTING

The majority of decision situations in soil remediation share important similarities. First, stakeholders evaluate a set of **remedial alternatives**, which represent the possible choices. The **objectives** to be achieved drive the design (or screening) of alternatives and determine their overall evaluation. Clearly the stakeholders in the made-up project do have different objectives. **Attributes** are the measurement rods – the decision makers ruler - for the objectives and specify the degree to which each remedial alternative matches the objectives. We have used these attributes in the second stakeholder meeting of the made-up project to show that the in situ alternative came very close to the objectives. Finally, **factual** information and **value** judgments jointly establish the overall merits of each option and highlight the best compromise solution (Beinat, 1997). Figure 3 summarises the information that plays a role in a multiattribute model. The information items are the multiattribute profiles ($A_1,..,A_m$) allowing measurement of the achievements of the (remedial) alternatives, the value functions ($v_i$, $i=1,..,n$) representing human judgments, the weights ($w_i$, $i=1,..,n$), and the multiattribute value function that associates an overall value with each alternative ($v(A_j)$, $j=1,..,n$).

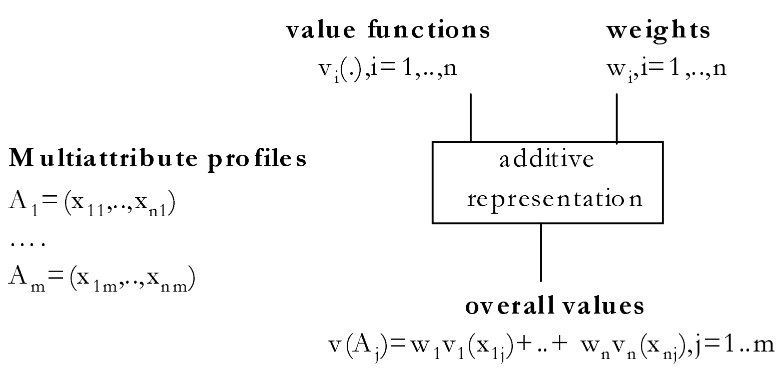


**Figure 3. Information items in a multiattribute model (Beinat, 1997)**

In this example, the overall merit of a decision alternative is computed as a weighted sum of single-attribute performances regarding all attributes. Although this evaluation scheme is very common and widely used, it is important to stress that it can be applied only under very precise conditions. Without going into this topic (see Beinat 1997 for an overview), it is sufficient to say that the additive rule can be applied only if independence conditions across attributes are met. This, in turn, calls for a careful structuring of the decision problems and a careful choice of the attributes.

Simple enough! Unfortunately different stakeholders often have different objectives and, thus, their multiattribute profiles, their functions and their weights are not identical. In our made-up project the stakeholders had different objectives, and their multiattribute profiles, functions and weights were different. Calculating an overall value for one stakeholder is possible, calculating one overall value for more than one stakeholder is only possible if objectives, profiles, functions and weights are identical. Consequently, what you normally get is an overall value or a score for a proposed alternative seen through the eyes of a particular stakeholder. Agreement in our project is not only reached by the fact that the objective attribute scores were more identical than expected, but also because we managed to unify the multiattribute profiles a little. In other words: the stakeholders gradually agreed upon the selection criteria.
Not all of the attributes can be expressed in the form of some number and often these attributes will not be explicit. In other words, the overall quality of an alternative within a specific decision context is a function of the explicit and implicit attributes. This function can in turn be explicitly or implicitly used for negotiations between actors. In formula:

$$v(A_j) = f\,(w_1 v_1 (x_{1j}), .., w_n v_n (x_{nj}), \textit{implicit values})$$

Where *v(A)* is the quality of alternative A; $w_1v_1$ $(x_{1j})$, .. , $w_nv_n$ $(x_{nj})$ the explicit values for that alternative; and *f* is the decision rule, explicitly or implicitly used. On this basis, there are several possible approaches to the decision on the basis of the multiattribute model outcomes. They can be broadly classified as shown in Table 1.

**Table 1. Possible uses of the multiattribute model outcomes**

| | Multiattribute model outcomes are sufficient to make a decision | Other factors contribute to the decision |
|---|---|---|
| The decision rule is explicitly known as a function of attributes. | (**1**) The alternatives are evaluated by applying the decision rule and are ranked from best to worst and the decision is reached through analysis and evaluation. | (**2**) The alternatives are evaluated by applying the decision rule and are ranked from best to worst. The decision rule can than be extended to include other aspects and the decision is reached through analysis and evaluation. |
| The decision rule is not made explicit. | (**3**) The evaluation of alternatives is based on the multiattribute model outputs, but the pros and cons are discussed between stakeholders and the decision is reached through expert judgment or bargaining and negotiation. | (**4**) The evaluation of alternatives is based on the multiattribute outputs and on additional attributes, but the pros and cons are discussed between stakeholders and the decision is reached through expert judgment or bargaining and negotiation. |

# 4. TOOL 1: BEST AVAILABLE TECHNIQUES

## 4.1. SEARCH AND SCREEN (AND ANALYSIS/EVALUATION) SUPPORT

BAT (Best Available Techniques) is an MS-Access/Virtual Basic product for Windows. Tauw and VITO (Flemish Institute for Technology Development) have developed it. BAT is a decision support tool that is aimed at supporting soil remediation experts, policy makers and environmental managers (Gevaerts et al., 1998).

The knowledge base of the tool consists of a large number of factsheets related to remedial concepts and techniques. As input BAT requires four types of information: soil characteristics, contamination characteristics, other characteristics such as presence of buildings and infrastructure and, finally, remedial targets and duration. As soon as the input is entered the tool starts to compare the input data with the factsheet data and the output is a list of suitable concepts and techniques, unsuitable concepts and techniques, concepts and techniques for which a decision requires additional data and, finally, concepts and techniques which are not relevant to the problem described.

For soil remediation experts the tool supports during the **search** and **screen** routines of a modified search or dynamic design decision process and as such it is related to the development phase of the decision process. Its goal is to give the user an overview of remedial alternatives that could be worked out. For policy makers and environmental managers the tool enables to check the work of environmental experts. As check it is probably more in line with the **screen** and **analysis/evaluation** routines and thus with the selection phase of the decision process. Note that in case of second opinion soil remediation experts can use the tool to check the work of their colleagues.

## 4.2. FEEDBACK AND FEEDFORWARD

The selection of a number of possible remedial alternatives is an important stage in the process. Although trying to anticipate to the preferences of the stakeholders by presenting a specific subset of the outcomes of the BAT model is possible, we feel that the total set of outcomes of the BAT model should be discussed with the stakeholders. This may tempt the stakeholders to change their preference profile, and, as a designer you can never be accused of having a narrow scope. Thus, when using the BAT model within the decision process we recommend not using the feedforward paradigm. After the results have been discussed in the selection phase of adaptive decision processes such as the modified search or the dynamic design decision process the ‘lessons learned’ should be included in the next iteration.

As has been discussed before our target is not the decision process, but the effect and the efficiency of the resulting action. If we stretch our attention to the remedial actions, then we can make use of the experiences with the remedial alternatives. These experiences should be included in the knowledge base of the tool, i.e., in the factsheets. This kind of feedback requires clear guidelines for the maintenance of the model. If the outcomes of certain remedial alternatives are more uncertain than those of others, then this should be communicated. This kind of feedforward/anticipation (see Okx and Stein, 2000) should avoid disappointment.

## 4.3. THE MULTIOBJECTIVE SETTING

The BAT models goal is to give the user an overview of remedial alternatives that could be worked out. In this stage the decision rules are not made explicit yet, and other factors than those used by the model do contribute to the decision. Thus, the evaluation of alternatives is based on the model outputs and on additional attributes, but the pros and cons are discussed between stakeholders and the decision is reached through bargaining and negotiation.
Our observation is that in this stage the legal authorities are seldom involved, and discussions are held at a technical level. This should be considered as a missed opportunity. Discussions like ‘what if that and that

happens' are most valuable and could result in modified solutions capable of handling less likely situations as well as the expected situation.

# 5. TOOL 2: IN SITU AIR SPARGING

## 5.1. DESIGN SUPPORT

In situ air sparging – A technical guide, Version 1.1 has been developed by Tauw and GeoDelft. We gratefully acknowledge the views and comments of many people, in particular Terry Walden of BP Oil Europe UK and Rick Johnson of Oregon Graduate Institute in the United States. The technical guide is a tool for consultants/designers to help plan the remediation process and to design and operate an in situ air sparging (IAS)/soil vapour extraction (SVE) system. The guide should be able to support decisions for the clean-up of different types of sites ranging from small sites with permeable soil to large industrial estates with strongly heterogeneous and stratified soils (Pijls et al., 2000). Its predecessor – Version 0.1 – had a totally different appearance. It was structured around a large number of flowcharts and meant to lead the expert via a series of questions to an optimal design. Its structure was ideal for the envisaged software implementation. During the test period, however, the future users rejected the product for two reasons:

- They preferred a reference guide rather than some kind of workflow oriented tool; and
- They were questioning the systems ability for special cases.

Although I am still not convinced whether it was the only option, we decided to capitulate and developed the classical technical guide. We were reported that in the same period a similar project in the United States faced a similar fate (Leeson et al., 1998).
The present tool is organised in a number of chapters covering: the theoretical background, remediation concepts, feasibility studies, design, hardware/equipment, installation of the IAS/SVE system, operation of the IAS/SVE system, shutdown and postclosure measures and costs. Thus, it follows more or less the designers' logical steps. However, if the designer has a particular question on blowers and compressors, then he can skip everything except the section on injection equipment In Version 0.1 skipping sections was less easy.
For soil remediation experts the tool supports during the **design** routine of a modified search or dynamic design decision process and as such it is related to the development phase of the decision process. Its output is a detailed IAS/SVE design.

## 5.2. FEEDBACK AND FEEDFORWARD

IAS/SVE design takes place after the selection of a number of remedial alternatives by the stakeholders. Again I feel that all possible options in IAS/SVE should be discussed, but, as long as technical choices do not lead to different results, not all of the stakeholders need to be involved. The processes induced by IAS/SVE are rather complicated, and, in order to discuss items such as blowers your discussion partner should have some knowledge about lateral rotary blowers, rotating lobe blowers, rotary sliding vane blowers, and so on. Selection is based on expert judgment rather than on analysis or bargaining. Thus, when using the technical guide in a modified search or the dynamic design decision process the expert judgment or 'lessons learned' should be included in the next iteration.
If we stretch our attention to the remedial actions, as we did with the BAT model, then we can make use of the experiences with IAS/SVE concepts, feasibility studies, design features, hardware/equipment, installation, operation, postclosure measures, and costs. These detailed experiences should become part of the next versions of the technical guide. This kind of detailed feedback requires even more clear guidelines for the maintenance of the guide. Again negative and positive experiences allow for anticipation.

## 5.3. THE MULTIOBJECTIVE SETTING

The IAS/SVE guide supports IAS/SVE design. In this stage the decision rules are connected to the implicit knowledge of experts, and other factors than those used by the guide do practically not contribute to the decision. Thus, the evaluation of alternatives is based on the model outputs, but the pros and cons are discussed and the decision is reached through expert judgment. Our observation is that legal authorities are seldom involved in this stage, and discussions are held at a technical level. As long as technical choices are unlikely to change the effect and efficiency of the clean-up operation, it should not be considered as a missed opportunity.

# 6 TOOL 3: COMPARISON OF REMEDIAL ALTERNATIVES

## 6.1. Analysis/evaluation support

REC is an Excel/Virtual Basic Decision Support Tool for Windows for the analysis and evaluation of possible clean-up strategies for a contaminated site. REC was developed by Tauw, the Institute for Environmental Studies of the Free University of Amsterdam and Berenschot Osborne of Utrecht. The aim of REC is to support the choice of the most effective and efficient strategy for soil remediation in terms of risk reduction, environmental merit and costs for the site concerned (Okx et al., 1998; Okx, 1999).

The core of the model consists of a database comparable to those of Life Cycle Analysis (LCA) tools and a large number of formulas able to calculate risk, reduction, environmental merit, and costs. As input REC requires three types of detailed **design** data of the chosen remedial alternatives: risk characteristics such as type of contamination, risk profile, land use, the area involved, environmental characteristics such as expected amount of clean ground and ground water, use of resources like clean ground, ground water and energy, air emissions, pollution of surface water, production of final waste and spatial occupation, and, finally cost characteristics such as preparation costs, demolition costs, remedial costs, replacement costs and discount rate. The output of REC is a set of three indices for each clean-up alternative: the risk reduction index, the environmental merit index and the costs index. Together, these indices summarise the overall performances of each option (see Figure 4).

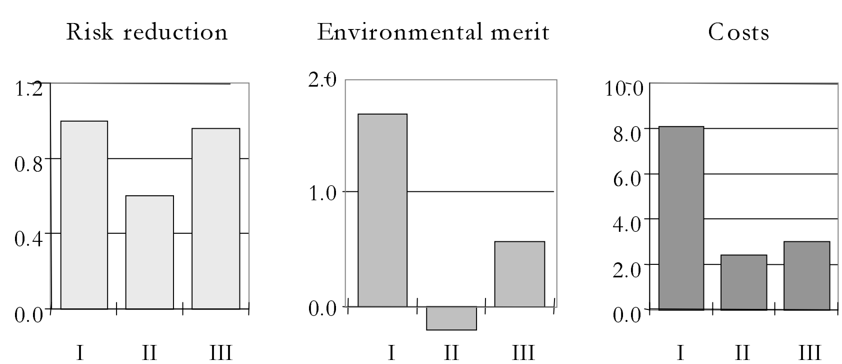


**Figure 4. R-, E- and C-indices of three remedial alternatives I, II and III**

Thus, the tool supports the **analysis/evaluation** routine and, thus, is linked with the selection phase of the decision process.

## 6.2. FEEDBACK AND FEEDFORWARD

The selection of the remedial action is seen as the most important stage in the process. In general the decision rules of the different stakeholders are known. Three strategies are quite common: a focus on effectiveness, which aims for the selection of the most effective option provided the budget available is sufficiently high; a focus on costs, which aims for the selection of the cheapest solution provided some significant risk reduction is achieved; and, finally, a focus on efficiency, which aims for the selection of the solution that gives the best ratio between risk reduction, environmental merits and costs.

We saw in practice that the designers who worked with REC developed – by using the models feedback – a feeling for the relation between design features and the R-, E- and C-indices and they gradually developed into designers able to anticipate the results of the REC model. Their designs became smarter: an advantage of the use of the full-information paradigm.

Stretching our attention to the remedial action means that we will be able to improve the LCA-like database of the tool, and that the model will improve steadily. Again we need to organise this kind of feedback. If we don't we will not benefit from our experiences. If the outcomes of certain remedial alternatives in terms of the R-, E- and C-indices prove to be uncertain, then this should be communicated. The present model presents the cost uncertainties.

## 6.3. MULTIOBJECTIVE SETTING

The REC model gives the stakeholders user an overview of the consequences of remedial actions in terms of risk reduction, environmental merit, and costs. In this stage the stakeholders have their decision rules set, but are not always willing to expose them. Other factors than those used by the model do contribute to the decision. Thus, the evaluation of alternatives is based on the model outputs and on additional attributes, but the pros and cons are discussed between stakeholders and the decision is reached through bargaining and negotiation.

Our observation is that in this kind of analysis/evaluation routines the legal authorities are nearly always involved. Although the multiattribute profiles and specially the weights attached to the attributes differ for the stakeholders involved, our experience is that quite frequently one alternative outclasses the others regardless of profiles, weights and values. Such an alternative is easily accepted by all of the stakeholders, which gives them almost a co-responsibility for the chosen alternative. Note that co-responsibility is not the same as co-liability! Discussions like 'what if that and that happens' are again a common feature and frequently result in modified solutions capable of handling less likely situations as well as the expected situation.

## HAPPILY EVER AFTER …

There are many tools, which supports the decision process. In this article we have shown only a few of them: a tool that lists the best available techniques for the problem at hand, a tool that enables IAS/SVE design, and, finally a tool that enables to select the best design on the basis of risk reduction, environmental merit and costs. Presently the tools are used independently of each other, but signs of integration by using feedbacks and feedforwards are observed. The case of the REC using designers give rise to a project trying to formalise the design rules which were implicitly used by our designers. Once these rules are explicit, they should be fed to tools such as BAT or the IAS/SVE guide. The reduction of the designers' degrees of freedom, however, should be avoided. This can be realised by simply enabling the users of the tool to switch the rules off or on. In my opinion this kind of development does not mean that we should aim for an all-including integrated decision support tool which does it all. Instead we should develop a number of smaller tools that are almost invisibly interlinked by feedbacks and feedforwards, but they have to be used independently of each other. The boundary of the decision process as described by Mintzberg does not include the actual actions, and this inhibits a gradually improving decision quality. Feedback and feedforward should include the actions. If not, then a proper evaluation of our decisions will remain impossible. Involving the stakeholders in the decision process is necessary and beneficial. An alternative accepted by all of the stakeholders, is the best alternative.

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# CASE STUDY: COST BENEFIT ANALYSIS / MULTI -CRITERIA ANALYSES FOR A REMEDIATION PROJECT

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**SUMMARY**

Transparent planning processes are necessary to increase acceptance of remediation projects with the general public and those affected. Compared to simple cost estimates, an evaluation of remediation schemes, compatible with the space, that is carried out using an economic and ecologic assessment of a remediation concept can ensure a uniform comparison of various remediation measures. Further planning may then be carried out on that basis.

The following instruments are used when preparing an overall remediation concept that is compatible with the site in the planning phase of a remediation scheme:

1. A dynamic efficiency calculation considering also – expressed in monetary terms – the loss of use of a contaminated site and the duration of the remediation measure, and
2. A value in use analysis of the ecological effects of a remediation scheme.

This results in a scope for decision, which ensures optimal planning results for the remediation concept. This scope relates to identifying the optimal economic and ecologic remediation solution in each case for the remediation process to be used in a particular case of damage. The economic costs and the ecological benefits of a remediation concept need to describe the effectiveness and/or compatibility with the site of a remediation scheme and thus allow justifiable decisions to be made.

## 1. INTRODUCTION INTO THE ECONOMIC AND ECOLOGIC OPTIMISATION WHEN SELECTING REMEDIATION PROCESSES

When following a line of action in the remediation planning that is compatible with the site the selection of the remediation process or method used is optimised by the technical, economic and ecologic requirements in an iterative process. Alternative possible uses are considered to come to a solution that is economically and ecologically viable. As a rule, the owner of the land is free to define the target parameters for the remediation of contaminated sites within the given general statutory and technical conditions (see figure 1). In this, steps to avoid dangers for a non-sensitive use represent the lower limit (minimal concept). In enhancement of the ecological use of a remediation can even lead to the realization of a maximum concept that would allow universal subsequent use under even the most sensitive requirements.

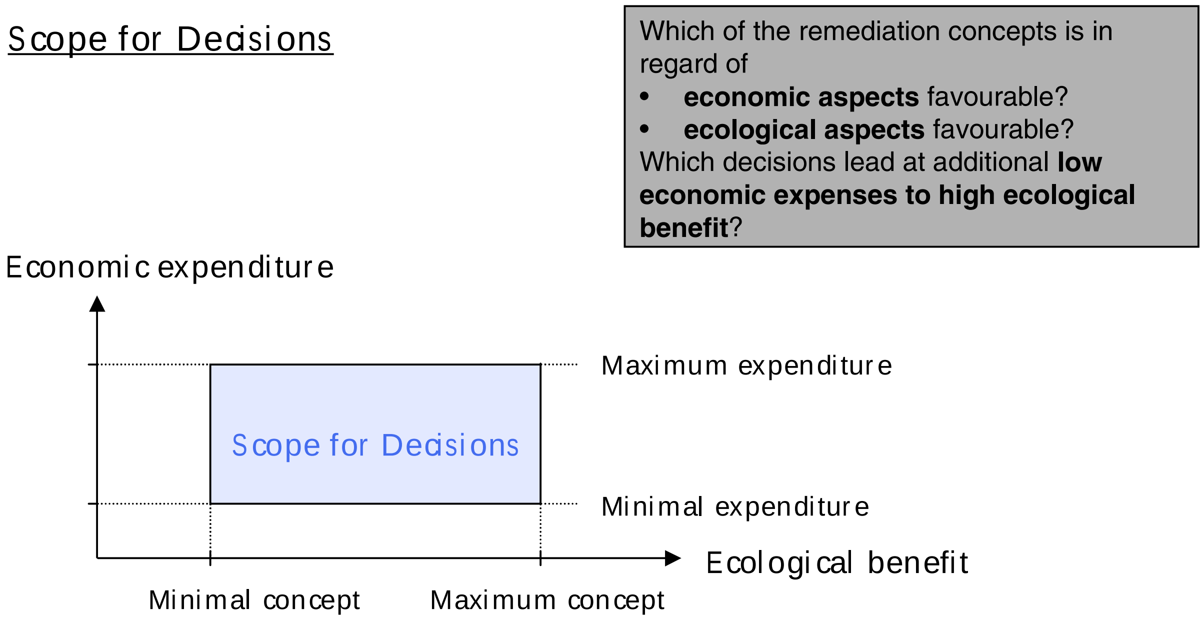


**Figure 1. Scope for Decisions**

Taking into consideration the avoidance of danger the following criteria need to be considered when selecting the remediation process and/or a combination of processes in addition to the *costs*:

- Precedence of the destruction of harmful substances over separation
- Minimizing masses and mass flows
- Waste avoidance, minimizing residuals
- Substance recycling
- Resource conservation

To evaluate the remediation concept in terms of its economic and ecological aspects, all technically feasible remediation processes together with their costs and uses in the form of ratios need to be included as alternatives in the decision making process, in order to provide as wide a base a possible for arriving at a decision (Gehrke 1993).

## 2. ECONOMIC VALUE LEVELS

The remediation processes that could be used need to be assessed in respect of their economic value levels:

**Table 1. Economic value levels**

| Value level | Description | Process | Efficiency calculation approach |
|---|---|---|---|
| Cost level | Costs of the remediation process | Comparative cost method | static |
| Expense level | Benefit due to increased value of decontaminated site | Comparative profit method | static |
| Investment level | Costs due to different lengths of time needed for remediation | Capital value method | dynamic |

(according to Gehrke 1993)

The costs of a remediation process, however, depend primarily on the amounts to be treated. In addition the various fix costs for site setting up and safety at work need to be taken into account (see figure 2).

**Cost comparison calculation**

| | | |
|---|---|---|
| $m_i$ X $k_i$ | = | Sum of the quantity dependent method costs |
| $i$ | = | Index for different remediation methods |
| $m_i$ | = | Contaminated soil and groundwater quantity |
| $k_i$ | = | Method specific quantity dependent cost attempt [$/m³] |

**Figure 2. Cost comparison calculation**

On the other hand, varying revenue is obtained as a consequence of a remediation, in particular revenue derived from subsequent use of the remediated site, but also the avoidance of higher remediation costs at a later date, the enhanced image of the landowner or the avoidance of claims for damages put forward by the owners of adjacent land that would be affected by the pollution spreading. The revenue from any subsequent use is important and can be assessed from a business costing point of view and it needs to be compared to the costs of carrying out the remediation.

The alternative remediation options can differ widely as regards the duration of their use. A significant influence on the economic results, which is calculated by the capital value method is brought to bear by the

- loss of interest due to having to pay procedural costs
- loss of interest due to lost monetary use of the site

(Figure 3). The capital value is composed of the following elements:

1. Costs of the procedure
2. Loss of monetary use due to a permanent limitation of the use of the building plot on completion of the remediation
3. Loss of interest due to varying durations of the measures, and
4. Loss of interest due to the varying length of occupation of building plots (Gehrke, 1993)

**Capital value method**

Capital value:
- Method costs
- Loss of monetary due to a permanent limitation of the use of the building plot on completion of the remediation
- Loss of interest due to varying durations of the measures
- Loss of interest due to the varying length of occupation of building plots

Calculation of the capitel value:

| | | |
|---|---|---|
| K(t) | = | $K(t{=}0)\ X\ [\ 1 + r\ ]^{n}$ |
| K(t) | : | Capital value at the time of (t) |
| r | : | Internal interest rate |
| n | : | Period |

**Figure 3. Capital value method**

The economically most advantageous process is that which yields the maximum final sum in relation to the alternatives. The criteria of advantage for a comparison of the alternatives is therefore:

- An investment I is more advantageous that an alternative II, if its negative capital value is smaller than the negative capital value of alternative II (Gehrke 1993).

## 3 ECOLOGICAL VALUE LEVELS

Soil and groundwater remediation is carried out to change the state of the contaminated site to such an extent that they do not pose a risk in respect of the use of the property/assets to be protected. Assets to be protected are primarily people's health. Carrying out a remediation project, however, also involves other affects. Two value levels should therefore be distinguished for an evaluation (see figure 4):

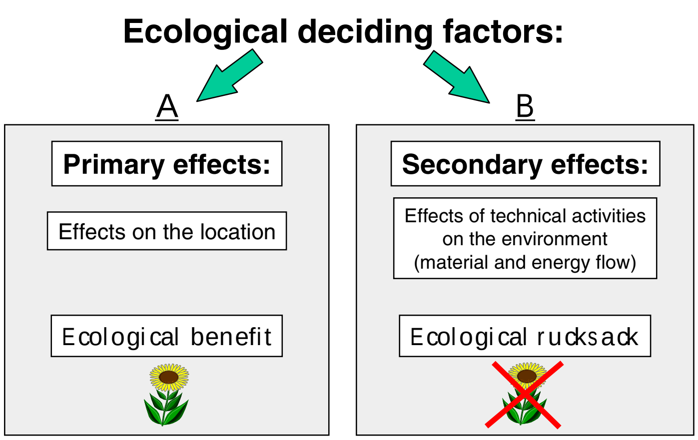


**Figure 4. Ecological value levels**

Primary effects = effects caused by the measurements on the environment of the site (figure 5)

- Quality and structure of the soil
- Biotope quality
- Groundwater quality and recharge
- Topography/relief
- Climate regulation potential

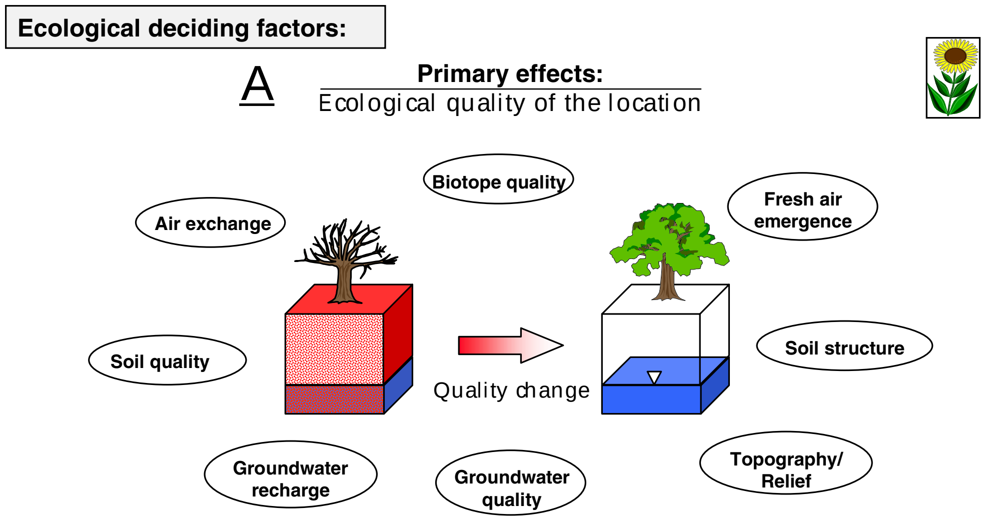


**Figure 5. Primary effects**

The individual primary ecologic effects (Figure 6) are ranged and weighted in relation to the local conditions.

1. Secondary effects = ecologic rucksack (supra-regional effects through the technical activities of the use of the process on the environment) (see Figure 7):

- Substance streams
- Energy streams
- Damage to the environment and health

**Ecological deciding factors**

**Assessment of the results of remediation measures**

| Criteria | Degree of the attainment of targets | Weighting | Result |
|---|---|---|---|
| **Condition improvement in the concerned media by remediation**<br>Soil quality<br>Soil structure<br>Topography/relief<br>Groundwater recharge<br>Groundwater quality<br>Fresh air emergence<br>Air exchange<br>Biotope quality<br>**Level of the method conditional remaining loads**<br>**Risks by the remaining loads**<br>**Durability of the success of the remediation measure** | | | |
| | | **Ecology value I** | |

**Figure 6. Ranging and weighting the primary effects**

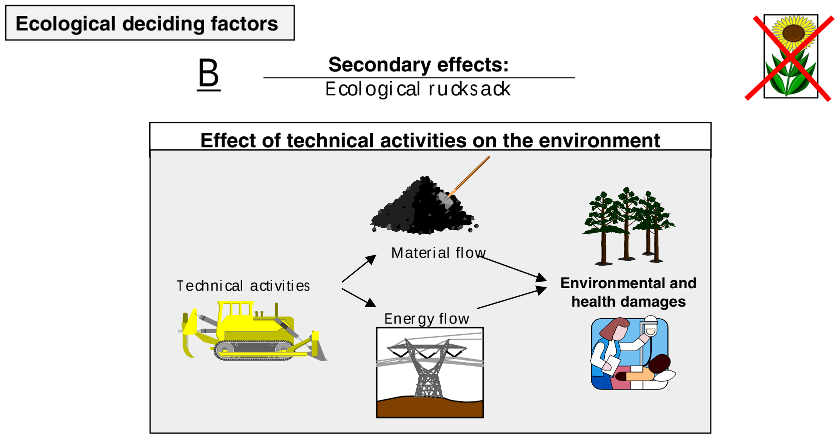


**Figure 7. Secondary effects**

With the secondary ecological effects too a weighting is done before both levels are combined into one ecologic value (Figure 8).

**Ecological deciding factors**

**Assessment of the execution of remediation measures**

| Criteria | Degree of the attainment of targets | Weighting | Result |
|---|---|---|---|
| **Waste and sewage issues** | | | |
| Waste disposal | | | |
| Sewage elimination | | | |
| **Protection of the human health** | | | |
| Air emissions of contaminants | | | |
| Dust issues | | | |
| Water emissions of contaminants | | | |
| Noise issues | | | |
| **Resource saving** | | | |
| Energy | | | |
| Additional chemical substances | | | |
| Natural raw materials | | | |
| | | **Ecology value II** | |

**Figure 8. Ranging and weighting the secondary effects**

The procedure followed when developing the ratios is a follows in the context of the comparison of procedures:

1. Defining an objective for the problem to be investigated
2. Translating an objective into evaluation criteria
3. Subjective weighting of the criteria according to certain comprehensible and controllable rules
4. Evaluation of alternatives based on profit targets

The effects that can be felt vary in the extent to which they occur both as regards quality as well as quantity. By using the ‘value in use analysis’ the effects on the environment are represented in the form of ratios and can thus be compared.

## 4. CONCLUSION

The model makes clear the connection between the economic effort and the ecological benefit of a remediation concept (figure 9). The ecologically best overall remediation concepts consists of the process alternatives with the smallest capital values with the benefit as a result of an increase in value of the rehabilitated site and the costs due to the varying timescales of the remediation also being taken into account in addition to the costs for the remediation scheme itself. The ecologically best overall remediation concept is expressed by the highest values in use. These result on the one hand from the extent and the sustainability of the improvement of the state in respect of the exposition of human beings and the environment by the remediation measure and on the other from process related environmental pollution by the remediation project itself, which have supra-regional ecologic effects.

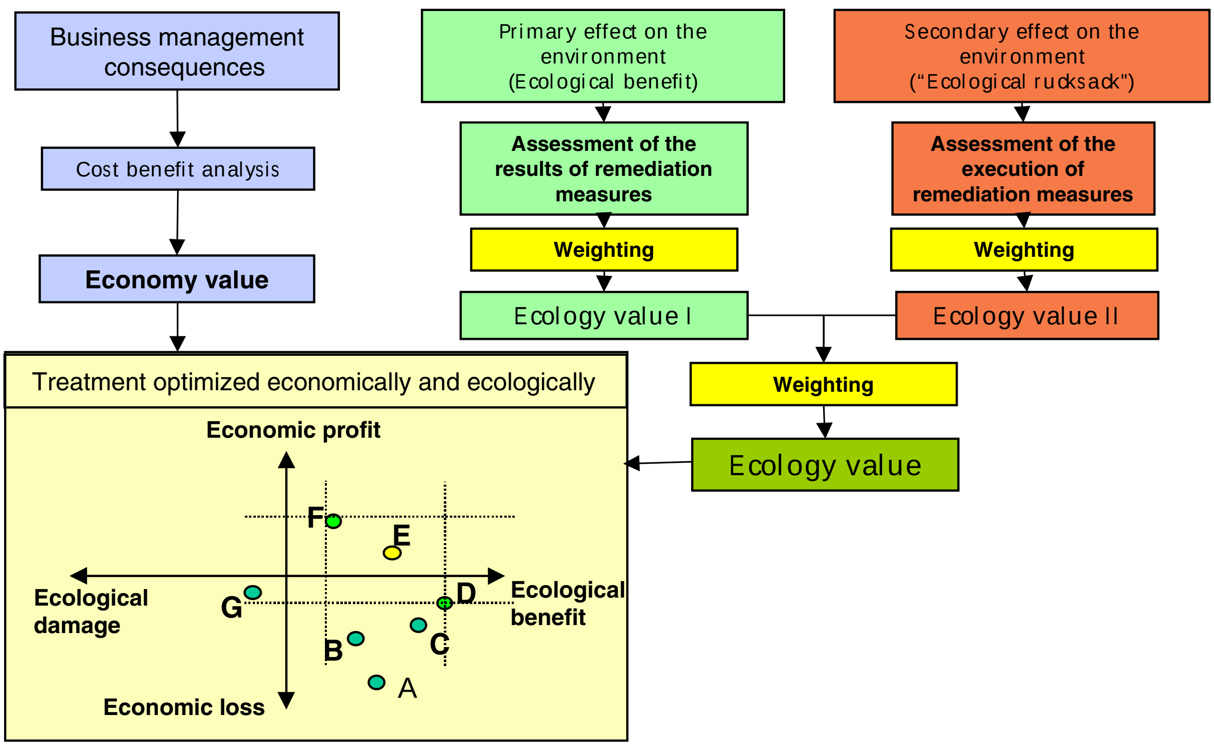


**Figure 9. Treatment optimized economically and ecologically**

The combination of the ratio pairs of the investigated remediation concepts is illustrated by the two extremes – the ecologically best concept that does not take into account economic considerations (Figure 9; case D) and the economically most advantageous concept, which does not consider the ecological benefit (Figure 9; case F). Where the economically best remediation concept varies from the ecologically best scheme, a scope for decision results. Purely formally, that concept will show the best "economic-ecological effect" by which the ration of increase in ecological benefit to the increase in the capital value is the largest (Figure 9; case E).

When calculating the economic and ecological ratios there are naturally uncertainties. With the economic ratios these are largely the result of the risk of changes in the volume, for the ecological ratios they relate mainly to the previously relatively subjective setting of the objectives and the weighting that needs to be carried out. Those ratio pairs are decisive in the comparison of the results of several remediation concepts which, as regards the identified bandwidth are on "the safe side", i.e., the – in respect of the amount – smallest ecological benefit with the largest economic expenditure.

To be able to carry out the effectiveness of remediation measures in the context of the preplanning fast and transparently, we developed the DV supported effectiveness analysis model "WILMA". The economic and ecological standards can be described and covered with the corresponding code numbers so that the economic and ecological effectiveness of a remediation is determined.

With WILMA different use scenarios can be simulated in connection with location specific factors. The use scenarios of the redeveloped area depend on toxicologic examining results, in which we distinguish in:

- Children's playground
- Living use, general
- Park/public green space
- Fallow area
- Industry and trade area

At the moment we are able to carry the calculation with WILMA for the approx. 20 most important remediation methods. By the flexible conception of the model the standard details of the database can be adapted to regional conditions. An individual case obtained use of the planning instrument gets possible so. Prerequisite is an exact knowledge of the damage and this one for the location specific conditions essential for remediation and use.

## 5. SALZWEDEL CASE STUDY

Using WILMA a remediation involving a site contaminated with petroleum-derived hydrocarbons and BTEX (benzene, toluene, xylene) on the former helicopter port of the East German border troops at "Salzwedel - Fuchsberg" that has already been completed was subsequently calculated for calibration and testing purposes (see figure 10).

**Case study: "Salzwedel"**

**Helicopter base of the former GDR - border troops**

**Contaminations of soil and groundwater in the area of a gas station by kerosene,** diesel oil and gasoline

| Soil: | |
|---|---|
| Initial concentrations: | MKW up to 17.800 mg/kg<br>BTEX up to 200 mg/kg |
| Remediation aim: | MKW: 150 mg/kg<br>BTEX: 2,5 mg/kg |
| Volume to be redeveloped: | approx. 1.100 m³ |
| Soil type: | fine - middle grained sand |

| Groundwater: | |
|---|---|
| Initial concentrations: | BTEX up to 50 mg/l |
| Remediation aim: | BTEX: 20 $\mu$g/l |

**Figure 10. Case study 'Salzwedel' – Basic information**

## 5.1 BRIEF DESCRIPTION OF THE SALZWEDEL CASES

On the former filling station site mean petroleum-derived hydrocarbon concentration of 2,000 mg/kg (max. 17,800 mg/kg) and/or BTEX levels of approx. 200 mg/kg were found in the soil. The aromatic hydrocarbons had already entered the groundwater, which had BTEX levels of up to 50 mg/l. The soil contamination affected approx. 500 m², groundwater contamination affected approx. 5000 m². The volume of soil to be rehabilitated was approx. 1,100 m.

The site is partly used for residential purposes (renovation of the old barracks building), and part of it is derelict (still owned by the federal government) and used by a school.

## 5.2 RESULTS

As an initial step using the WILMA model a selection of the processes that could be used for the contaminants identified was made based on the details regarding the type and extent of contamination. After entering the site-specific soil properties and the available resources the program narrowed down the applicable processes. Resources are those site conditions that have a bearing on the construction or setting up of the remediation plant such as the necessary space (for the facility or for intermediate storage of soil, etc.), water, power, etc. Figure 11 shows the results of this pre-selection.

**Case study: "Salzwedel"**

**Possible remediation methods (MKW/soil):**

R Soil clean-up on-site
Soil clean-up off-site
Microbiological treatment on-site
Microbiological treatment off-site
K Microbiological treatment in-situ
Pyrolysis off-site
Incineration off-site
B Slot-wall
B Steel sheet-pile wall
B Depositing

**Possible remediation methods (BTEX/soil):**

R Soil clean-up on-site
Soil clean-up off-site
Microbiological treatment on-site
Microbiological treatment off-site
K Microbiological treatment in-situ
Pyrolysis off-site
Incineration off-site
Soil venting with active coal
Soil venting with catalytic oxidation
B Slot wall
B Steel sheet-pile wall
B Depositing

**Exclusion of the method by:**

R: Lack of location specific resources (available areas, water, energy etc.)
K: Location specific criteria (e.g. grain size, too low groundwater level referred to ground elevation)
B: Editor

**Figure 11. Case study 'Salzwedel' - Possible remediation methods**

After calculating the economic costs of the processes left and the ecological benefits, and after combining the individual processes the result shown in Figure 12 was arrived at.

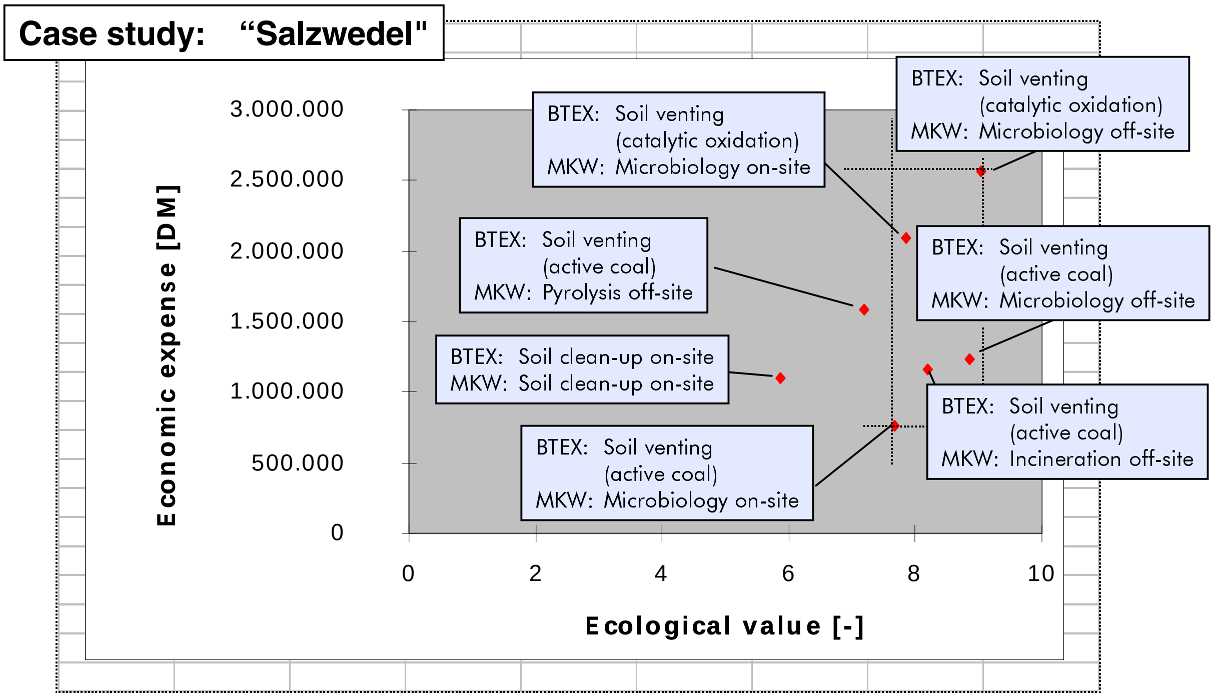


**Figure 12. Case study 'Salzwedel' – Results**

It became apparent that the combination of soil air extraction with cleaning of the extracted air by activated charcoal for eliminating the volatile BTEX from the unsaturated soil zone with a microbiological on-site process (clamp) – and when ignoring the ecological benefits – involved the lowest economic costs. On the other hand additional ecological benefits would only have resulted – involving a significant increase in the economic costs –from the combination of "soil air extraction with catalytic oxidation" with "microbiology off-site." This combination of processes showed the highest eco benefits when ignoring the economic costs. Cleaning the soil from the petroleum-derived hydrocarbons by means of a thermal process (off-site incineration) too would have meant a significant increase of economic costs at only small increases in ecological benefits due to the transport costs involved.

## 6. LIFE CYCLE ASSESSMENTS AS METHODS IN THE QUALITATIVE AND QUANTITATIVE EVALUATION OF ENVIRONMENTAL EFFECTS IN THE REMEDIATION OF CONTAMINATED SITES

Apart from the value in use analysis shown a further method for assessing the effects of the environmental pollution through the remediation project itself can be calculated by means of life cycle assessments.

In the 'value in use analysis' a methodological comparison of processes is made. Similar to the methodological steps of the environmental impact assessment under the UVP Act this involves the assessment of the ecological benefit and all the effects of the remediation scheme on the environment, which are described, forecast regarding both quality and quantity, assessed and summarized as a ratio, in order to obtain a comparison and be able to arrive at a decision as regards the selection of the method.

The 'life cycle assessment' too should take into account as far as possible ecological criteria when specifying possible remediation processes in order to achieve long-term ecological optimisation. For this it is necessary to know what effects the methods considered may have on the environment. The Federal Environment Office suggests the following definition of the term:

> *The life cycle assessment is a comparison, which is as comprehensive as possible, of the environmental effects of two or more different products, product groups, systems, process or behaviours. It serves to point out weak points, to improve the environmental properties of products, the decision making process in procurement and purchasing, to promote environmentally friendly products and processes, to compare alternative courses of action and to back up recommendations for action to be taken. Depending on the underlying question this comparison is supplemented by further aspects, e.g., an assessment of the environmental protection efficiency of funds. (from Schmidt-Bleek 1993)*

The Federal Environment Office suggest to standardize the method as follows:

1. step: Definition of the objective of the report

2. step: Operation balance: setting up a data basis by analysing all environmental influences on the lifecycle of a product starting with raw material procurement to disposing of the waste in life periods, the modules (vertical analysis). Considering the entries and exits of the modules in respect of the use of primary energy, raw materials, water and the emission into the air, the wastewater and solid waste (horizontal analysis). Examining the link between the modules (lifecycle criteria). Selection of the data.

3. step: Impact balance: Description of the impact of the substance streams covered in the operation balance on the environment.

4. step: Balance assessment

The concept centres on the method prepared on behalf of the LfU Baden-Wurtemberg, “Environmental balances of the remediation of contaminated sites” by C.A.U. GmbH.
Using this method it is possible, as has already been shown, to calculate remediation caused environmental effects as a result of an operating balance in which the potential effects, differentiated by certain impact criteria, has been calculated (Figure 13). In practice, however, the problem will often have to be solved as part of the necessary assessment of the balance, to weigh advantages and disadvantages of the individual remediation measures, in order to identify “the best possible method”. In cases where not one single method combines all the advantages over the other methods the person dealing with it at the building authorities is faced with difficult questions:

- Which disadvantages for the environment are so serious that any measures that include those disadvantages must be excluded as a matter of principle?
- Which environmental benefits balance out which disadvantages and to what extent?

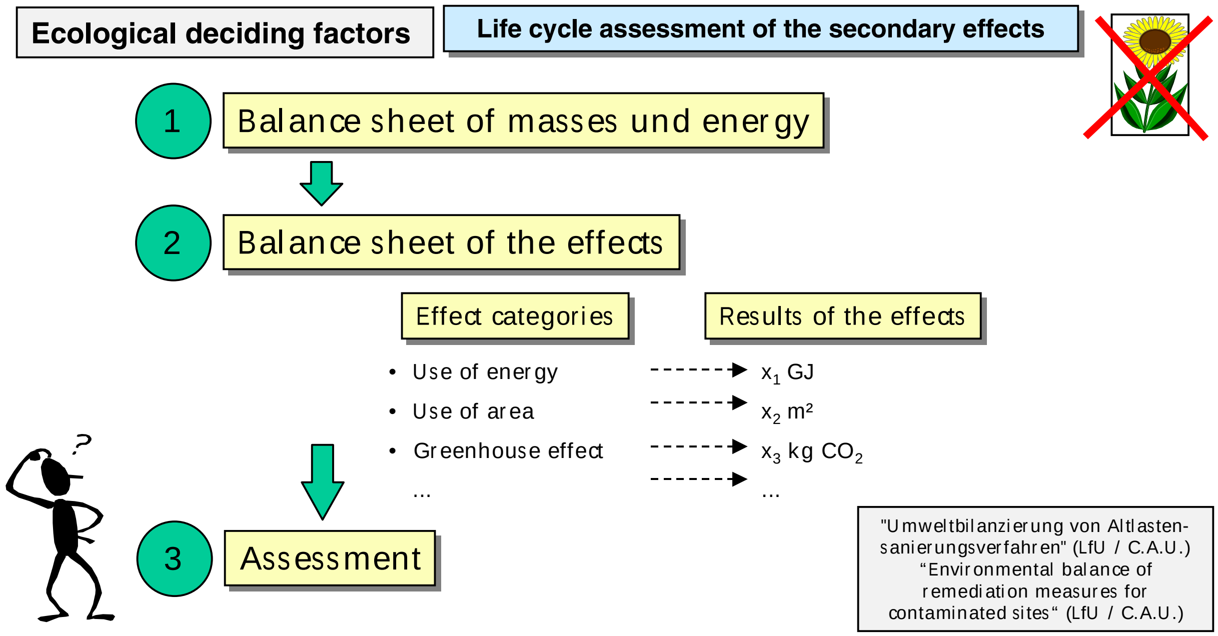


**Figure 13. Ecological deciding factors–Life cycle assessment of a measure**

A part objective is therefore to be able to calculate and overall index from the many indices calculated by means of the "CAU method", which allows a statement to be made on the best ecological remediation concept.

To do so it is necessary to obtain cost factors that are as objective as possible for the individual impact categories of the CAU method which, by multiplying them with the result of the impact balance, yield the external costs of that particular remediation scheme (Figure 14).

So the key aspect of the model presented here is "monetarisation". Calculating monetary values for all relevant decision criteria allows a direct link and comparison of economy and ecology. Simply summing of the economic value, the ecological values I and II result in a quantitative basis for selecting the optimal remediation method from business and economic aspects. If it is possible to minimize existing uncertainties in the monetarisation no further weighting of the above mentioned elements is necessary, such as would be the case in an assessment in which verbal arguments are put forward to evaluate ecologic concerns.

In a further step standards have to be developed for comparing the primary and secondary environmental impacts that present the local effects of the scheme at the site in an objective way. This can be achieve by monetarising the primary effects:

- Quality and structure of the soil
- Biotope quality
- Groundwater quality and recharge
- Topography/relief
- Climate regulation potential

As a result a ratio for the ecological effectiveness of a remediation scheme is obtained that, again together with the economic ratio from the cost/benefit analysis, delivers an objective basis for the decision making process for the most effective remediation scheme.

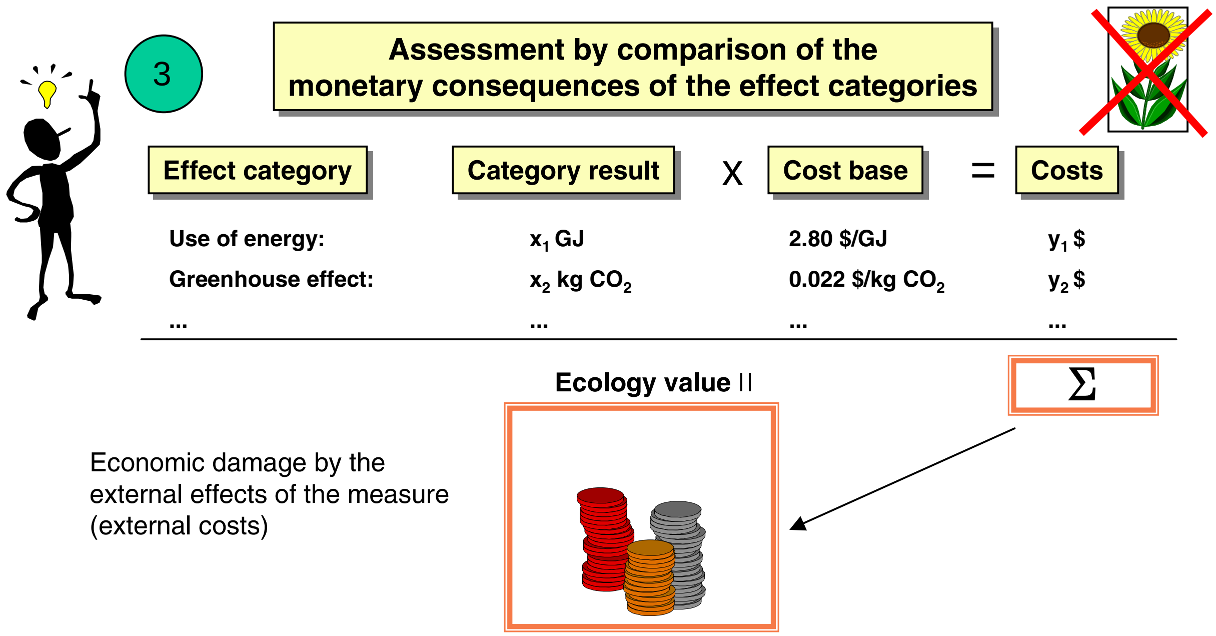


**Figure 14. Ecological deciding factors—Assessment by comparison of the monetary consequences of the effect categories**

## 7. SUMMARY AND CONCLUSION – ASSESSMENT OF THE RESULTS SO FAR

The results obtained by means of a value in use analysis in respect of the evaluation of any impact on the environment of the remediation of contaminated sites are well suited to a praxis-based comparison of alternative remediation methods. However, the weighting of the individual elements contained therein also reflects a subjective judgement. Contrary to that, a more "objective" from of evaluation could be carried out by a life cycle assessment plus subsequent monetarisation of the impact categories.

However, the results obtained from the various studies so far are based on different mathematical approaches (avoidance costs, damage costs, etc.), something which asks for criticism of aggregating the individual categories. The current state of environment economic research, however, makes it necessary to accept this mixture of methodologies. The problem of a "limited comparability" cannot be solved at the moment. For almost all impact categories taken into account there exist substantial gaps in research and that is the reason why the costs identified in many cases are not more than "rough estimates".

For these reasons we work with a value in use analysis to quantify the ecological consequences of remediation measures. One receives a two parametric result representation which serves as basis for the decision-making process.

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# MODELLING THE FINANCIAL RISKS OF REMEDIATION

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## ABSTRACT

The performance of remediation represents a significant source of financial risk, which, if ignored or mismanaged, can have a serious effect on the commercial success of a project or business. Risk management relies heavily on accurate forecasts of the probability that remediation will fail to meet its objectives as well as the associated financial implications - typically expressed as a reduction in net present value or internal rate of return. This paper discusses an analytical approach and methodology, based on stochastic modelling, to translate the technical risks of remediation into monetary expressions of risk. This approach provides an invaluable management tool that can generate real business benefits. Most importantly, commercial decisions - which inevitably require a company to take a risk - are made with greater confidence and certainty. There are then opportunities to optimise the management of risk by contractual mechanisms and structuring of project finance.

**Key Words**: commercial risk, financial forecasting, modelling, internal rate of return, net present value, expenditure, revenue, asset value

## INTRODUCTION

For many businesses, remediation of soil and groundwater has assumed greater importance through its potential to influence liquidity, solvency and overall financial performance. This trend is likely to continue throughout Europe as pressure mounts to re-use previously developed ‘brownfield’ land, a proportion of which will inevitably be found to be contaminated. Some companies view the role of remediation as simply protecting and maintaining asset (property) value whilst avoiding legal liabilities. Others recognise the commercial opportunities that remediation can generate in terms of enhancing the value of brownfield sites. Whatever the business case, there are corresponding financial risks relating to a company’s ability to meet its corporate and project objectives. These risks can have favourable and unfavourable effects depending on whether there is a downward or upward variation from the expected costs, revenue and asset value. The positive and negative variation can in turn cause a company to perform better or worse than expected.

The precise nature and extent of financial risk depends on the context in which remediation is undertaken. Where remediation forms part of an investment project, such as brownfield site reclamation, the underlying financial risk surrounds the internal rate of return (IRR) or Net Present Value (NPV). The IRR, which represents the return that can be earned on the capital invested in a project, can be greatly reduced to a point at which a project becomes non-viable commercially. The IRR reflects the volatility in the risk - the two factors tending to show a positive correlation (see Figure 1). NPV represents the present day cost of some action taken at some time in the future; in essence the present day value of that distant cost is discounted by the applicable interest rate over that period of time.

Remediation performance increasingly features as one of the principal sources of project risk and uncertainty to which organisations involved in brownfield development and reclamation are exposed. Thus, lenders providing finance on built projects (i.e., which do not involve remediation) will generally set a floor IRR (i.e., a minimum rate of return) that is lower than the rate for a brownfield reclamation, other factors being equal (see Figure 1). Interestingly, lenders in the UK do not necessarily set different rates of return for similar projects on brownfield sites and land that has not been previously developed

(Finnamore et al, 2000). Instead, borrowers are normally required to demonstrate increased levels of due diligence and risk management where contamination is a known or perceived issue.

Where remediation forms part of a defence plan to avoid liabilities, the principal risks surround escalation in costs and the realisation of liabilities if the remediation fails to meet the risk management objectives. Of particular concern are potential third party liabilities for bodily injury and property damage, which can cause unlimited financial impact. There are also knock-on effects in terms of reduced confidence amongst a company's stakeholders, which can translate directly into reduced share value or indirectly into increased cost of future financing and insurance. Independent research carried out on behalf of Citibank suggests that around 70% of a company's net worth is determined by the markets' perception of the company.

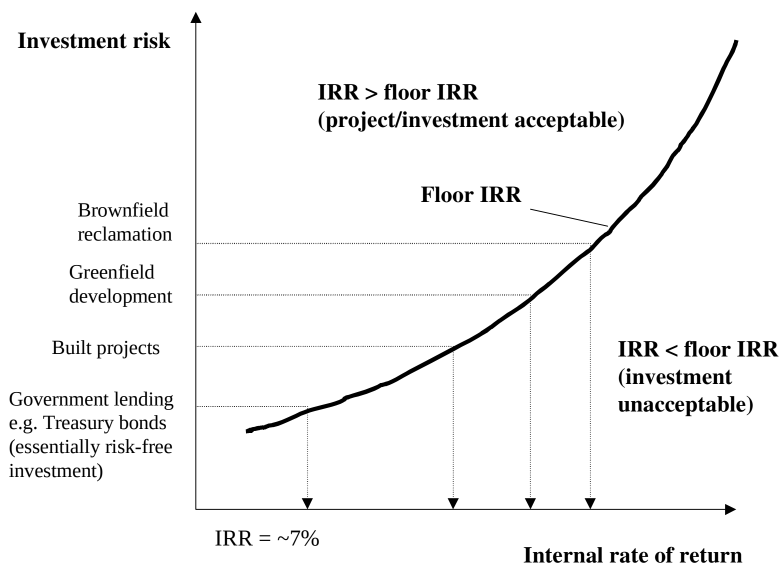


**Figure 1. Illustration of the relationship between IRR, project risk and project acceptability**

The effectiveness of remediation can be judged financially in terms of:

- meeting, or preferably beating, projected cost estimates (**project costs**)
- ensuring timely release of the property asset for income generating use (**revenue**)
- maintaining, or preferably, enhancing the value of the property (**asset value**)
- increasing the liquidity of the asset (**liquidity**)
- reducing/avoiding existing liabilities whilst avoiding creating new liabilities (**risk management**)

The financial risk associated with remediation stems from an inability, or perceived inability, to forecast its effectiveness in meeting these project objectives. The difficulty in forecasting this risk stems from the inherent volatility in, and complexity of, project costs and revenues, asset value, liquidity and risk management. The volatility is due to variation in remediation-specific factors and other external technical, scientific, regulatory, financial and economic factors. Certain variables are well understood and defined. Others show considerable natural variation that is poorly defined. Understanding these variables and the relationships that link them underpins any approach that seeks to forecast the financial risk of remediation.
Generally, the process of estimating the financial risks of remediation is improving, and will continue to do so. This is due in large part to growing experience of using various remedial technologies. Nevertheless, considerable uncertainty persists, whilst the levels of confidence that can be attached to financial forecasts show significant variation according to, amongst other factors, the technology under

consideration. This reflects the different uptake, application and, hence, experience of working with some technologies.

## FINANCIAL RISK ANALYSIS

The process of financial risk analysis for remediation is no different to the appraisal techniques applied to other project risks, and can be broken down into the following steps (Institution of Civil Engineers and the Faculty and Institute of Actuaries (1998).

### Risk Identification

The main objective of the risk identification stage is to identify events, which, if they arose, could threaten the achievement of the project's objectives. Such events are summarised in the form of a risk matrix, which outlines the risks that exist throughout the various stages of a project, along with the underlying causes. Each event can be triggered by one of more causes and can generate a number of financial outcomes, as illustrated in Figure 2.

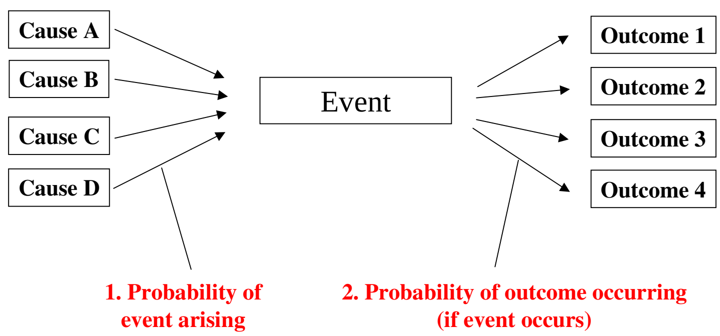


**Figure 2. The likelihood of possible outcomes (Institution of Civil Engineers and the Faculty and Institute of Actuaries, 1998).**

## 1. RISK EVALUATION

The risk evaluation stage generates forecasts of the impact of remediation risk on the financial performance of a project. The impact is analysed using bespoke financial models, which describe the financial performance of remedial technologies under multiple scenarios. The basis of each model is a series of algorithms. These describe mathematically the relationship between the variables which determine the probability of a risk event arising, as well as the probability and impact of the associated financial consequences (if the event occurs). Each model runs stochastically (probabilistically). Using this approach, discrete input values for variables are replaced by probability distribution functions (PDF's) which are sampled randomly many times by Monte Carlo simulation to build up a probability distribution of possible financial outcomes. The stochastic approach can avoid 'creeping' conservatism of deterministic models caused by sequential selection of 'worst-case' input values. However, stochastic models may suffer from systematic error caused by inaccuracies in constructing the model and defining PDFs for each variable or in generating the random numbers used to sample the PDFs.

The process of generating a financial model is illustrated in Figure 3.

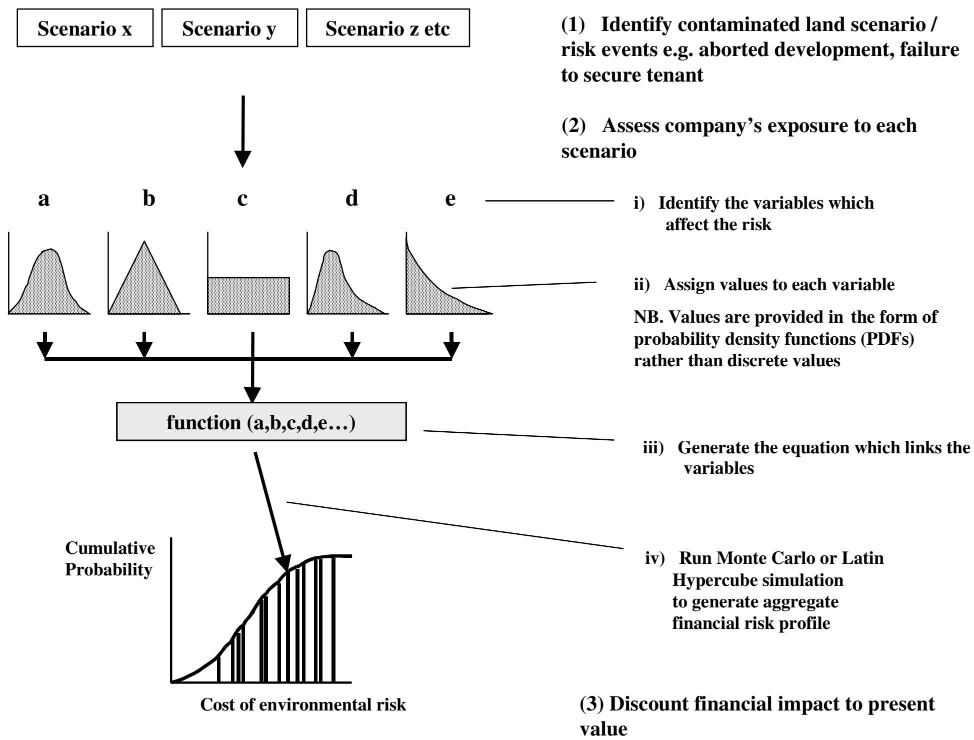


**Figure 3. Simplified illustration of the modelling process**

The structure and composition of the algorithms depends on the type of remediation and site/project specific characteristics. Algorithms are constructed by 'process mapping' remedial technologies and applying deductive methods. Alternatively, empirical or data-based methods may be used.

Process mapping breaks the remediation process down into various components, addressing inputs and outputs such as energy, waste etc. PDF's are assigned to variables based on:

- empiric data which relies on site-specific measurements and observations;
- default data from similar projects; or
- informed judgement

For remediation techniques that are relatively well understood, such as excavation and disposal, process mapping is relatively straightforward. In such cases, constructing the cost model algorithm and assigning PDF's is also relatively simple. For more complex remediation projects, or those involving innovative, untested process-based technologies, the process can be more complex and systematic errors are likely to increase. The use of probabilistic models in valuing contaminated land has been described by Kennedy, et al. (1996). In their work Kennedy et al built in uncertainty regarding remediation cost and duration in to a spreadsheet of NPV for the redevelopment of a fictitious site. They used Latin Hypercube Sampling (LHS) – a more computationally efficient variant of Monte Carlo (Nathanail 1994) for sampling the PDFs.

Critical model variables in terms of the importance of obtaining site-specific data include those relating to the nature and extent (lateral and vertical) of contamination. Interpolating from point information (such as trial pits or boreholes) to model the spatial distribution of contamination is frequently carried out using deterministic interpolators such as triangulation or inverse distance squared or by manual methods. Such approaches fail to adequately recognise the uncertainty in interpolation. Geostatistical techniques such as kriging do recognise this uncertainty and provide a qualitative indicator of uncertainty in the interpolation through the kriging variance. However kriging, in common with other weighted average interpolators, tends to smooth the raw data – effectively underestimating in areas of high values and overestimating in areas of low values. Geostatistical conditional simulations on the other hand preserve the variability in the original measurements and can be used to produce estimates of the probability of exceeding threshold values – such as risk based levels. Conditional simulations may therefore be used to inform cost models of the uncertainty in the extent and volume of contamination to be `tackled – and therefore the cost of remediation (Nathanail et al. 1998; Nathanail & Rosenbaum 1991).

Models are constructed in three sections - 'front end', processing and data presentation – reflecting the three functions of the model. The front end comprises a system for downloading information relating to the risk being analysed. The processing section of the model contains the algorithms that compute and 'score' the risks on the basis of the entered information. The data presentation component contains the macros that enable interrogation of the model.

## 1. FINANCIAL RISK MANAGEMENT

The findings of the risk analysis can be used to formulate an appropriate risk management strategy, typically based on a combination of risk control (reduction and mitigation) financing and transfer techniques. Two techniques are discussed below:

### a. Contractual risk transfer

In the example shown in Figure 4, the remediation costs of development are expected to be £10 million. The contract incorporates an excess layer of insurance, which covers cost overruns of up to £20 million for a premium of £1 million. The £1.5 million deductible is covered in full by the contractor, which puts all of its profits at risk. The problem holder bears the unlikely risk that costs exceed the insurance cover (i.e., any project costs in excess of £30 million, whilst sharing any cost savings (if the project costs less than £10 million) with the contractor according to a predetermined formula.

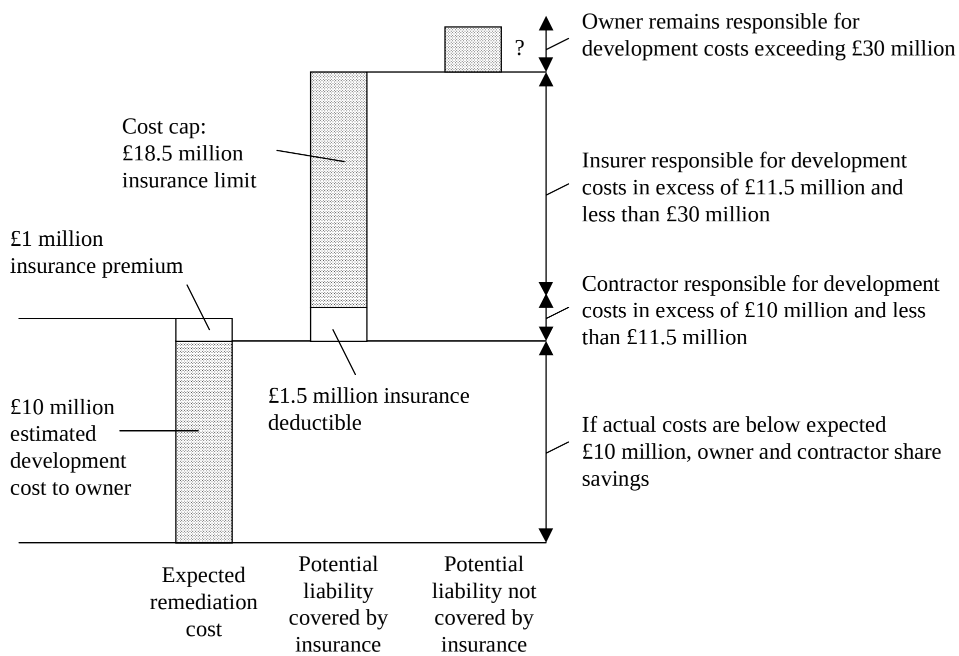


**Figure 4. Illustration of a risk sharing remediation contract involving insurance (Merkl, A and Robinson, H (1997)**

b. Insurance

Clean up cost cap policies indemnify the insured for remediation costs, as defined in the remedial strategy, that exceed a cost estimate agreed with the insurer. This value may be defined by modelling the remedial plan in order to express technical risks in financial terms. The policy attaches over a prescribed self-insured retention (SIR), which is generally equal to the expected costs of remediation plus a buffer layer.

Payment is triggered by increased projects costs caused, for example, by the discovery of unknown contamination or greater amounts of known contamination. Cover is also provided for extra costs to change the remediation works, in the event that the enforcing authority requires these changes. Cover may also be available for additional site investigation and any legal costs that could not have been reasonably anticipated under the remediation plan.

The buffer that is set will reflect the insurer's confidence in the insured's initial cost estimates and contingencies. The premium will normally depend on the cost and type of remedial work, the comprehensiveness of the remedial strategy and the amount of self-insurance.

**CASE STUDY: A Site in East London, UK**

*Background*

This case study is based on a site in East London, which was undergoing development for a combination of residential and light industrial purposes. A comprehensive site investigation had identified widespread contamination for which excavation and disposal had been put forward as an appropriate remedial strategy. A quantitative risk assessment had defined site-specific target levels (SSTLs) for remediation.

Using an investment model, the expected value of the project was £6 million based on future earnings from renting the commercial premises and from sales of the residential plots. The costs associated with development of the site were estimated at £4.5 million, including the purchase price of the land and construction costs, but excluding remediation costs. Thus the maximum potential net present value for the project was £1.5 million.

*Financial analysis*

The potential impact of remediation costs on the project NPV was simulated using a separate cost model. Based on site investigation data, the lateral and vertical extent of contamination was modelled using geostatistics. The outputs comprised a series of 3-d contour plots of contamination exceeding the SSTLs at various degrees of confidence. For each plot, the corresponding volume of soil (as measured in the ground) was calculated, creating an empirical probability distribution of contaminated soil volumes. In this case, the data approximated to a lognormal distribution, which was incorporated into the cost model. The re-use of clean, inert excavated material as backfill for other areas of the site was also incorporated into the model.

Examples of the variables on which the model was constructed are illustrated in Table 1.

**Table 1. Examples of the variables for the cost model**

| Variable | *PDF* | *Data source* |
|---|---|---|
| A. Quantity of soil requiring disposal | | |
| Volume of contamination exceeding SSTL (m3) | Lognormal | Empirical (based on geostatistics) |
| Excavation bulking factor (excavation) | Triangular | Default |
| B. Cost of excavation and disposal of contaminated soils | | |
| Distance to landfill site (miles) | Triangular | Site-specific data |
| Trimming and excavation charges | Uniform | Default |
| Volume of waste per lorry load (m3) | Triangular | Default |
| Disposal charge (landfill) (£ per m3) | Triangular | Default |
| Special waste consignment charges (£ per load) | Discrete | Default |
| Haulage rates (£ per m3) | Uniform | Default |
| Importation of clean fill material (£ per m3) | Triangular | Default |

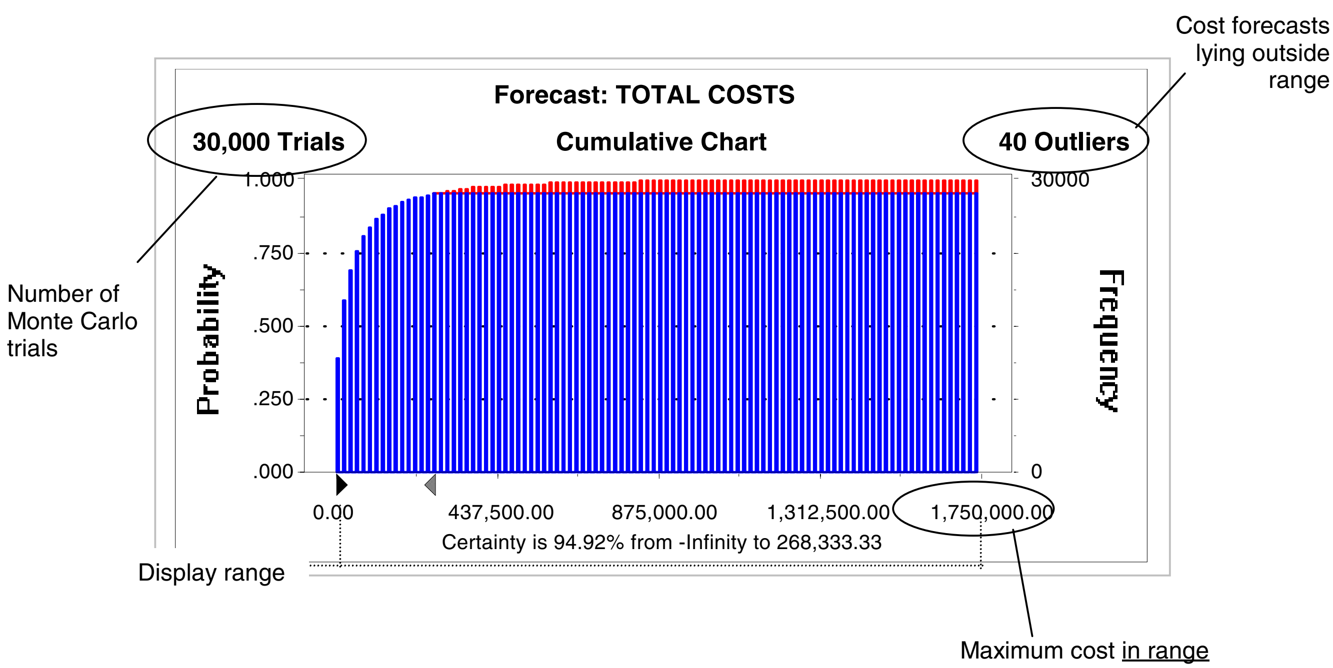


**Figure 5. Cost forecast chart**

**Table 2. Remediation cost forecasts and associated limits of confidence**

| *Limit of confidence in cost forecast (%)* | *Maximum remediation costs (£)* |
|---|---|
| 99.99 | ~4,800,000 |
| 99.9 | ~2,000,000 |
| 99.6 | 1,500,000 |
| 99.0 | 702,000 |
| 95.0 | 270,000 |
| 90.0 | 160,000 |
| 80.0 | 86,000 |
| 70.0 | 55,000 |
| 60.0 | 40,000 |
| 50.0 | 26,000 |
| 40.0 | 18,000 |
| 30.0 | 12,000 |
| 20.0 | 8,000 |

The results of the financial analysis of remediation costs were compared with the NPV generated by the investment model. The results of the analysis confirmed that at a level of confidence of 99.6% (representing a remediation cost forecast of £1.5 million), the remediation costs would not impact on the projected NPV to an extent that would make the project non-viable.

## CONCLUSIONS

Probabilistic modelling of remediation costs can be used to analyse the financial risks arising from land contamination and determining where the largest uncertainty and potential impacts on company or project performance are to be found. In this way remediation related risks can be managed in a way best suited to the organisation facing the risk and unforeseen consequences arising from land contamination can be minimised.

Detailed guidance tailored to the UK situation is forthcoming (Finnamore et al. 2000).

## ACKNOWLDEGEMENTS

The author gratefully acknowledges review comments received from Dr Paul Nathanail (Land Quality Management, UK) during the preparation of this paper.

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# DECISION SUPPORT USING LIFE CYCLE ASSESSMENT IN SOIL REMEDIATION PLANNING

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**Key words**: Decision support tool, environmental balancing, environmental management, life cycle assessment, planning, soil remediation, sustainability, "Umweltbilanzierung von Altlastensanierungsverfahren"

## ABSTRACT

Sustainable soil remediation shall be based on decision support systems that cover the evaluation of the environmental burdens caused by the remediation itself. The basic tool life cycle assessment can fulfill this task. Since the year 2000, all four elements of the life cycle assessment method are described by international standards (1SO 14040, ISO 14041, ISO 14042, ISO 14043). Since the year 1999, a life cycle assessment based tool is publicly available as software, which can help soil remediation planners to evaluate the environmental burdens of remedial actions itself. Today, a state of the art soil remediation planning tool-box includes life cycle assessment based tools.

## 1 INTRODUCTION

The requirement of sustainable development restricts the right to development (principle 3 of the Rio declaration on environment and development; UNEP, 1992). The right to development must be fulfilled so as to equitably meet developmental and environmental needs of present and future generations. One important issue in sustainable development is the management of soil. Soil management has often to tackle with contaminated soil. Many sites have been contaminated due to incompetent or criminal industrial or governmental management. Some sites are additionally or primary contaminated due to military industrial activities or military actions. Table 1 lists some contaminated sites and some soil pollutants.

**Table 1. Some contaminated sites made by NATO or NATO member states**

| Contaminated sites made in peace | Contaminated sites made in war (UNEP, 1999) |
|---|---|
| Kelly Airforce Base, San Antonio, Texas, USA: hydrocarbons (BMBF, 1996) | Pancevo (Serbia) "HIP Azotara" fertilizer plant and "HIP Petrohemija Pancevo" petrochemical plant, waste water canal to Danube and Yugoslavian, Romanian and Bulgarian Danube (4 April - 7 June 1999): 2,1 gigagram 1,2-dichloroethane (EDC), 8 Megagram mercury, oil, chlorinated solvents, depleted uranium |
| Building 360 at Naval Air Station Alameda (California, USA, Department of Defense): chloroethene compounds (NATO, 1999) | Kragujevac (Serbia) Zastava car plant (9 - 12 April 1999): 1 Megagram polychlorinated biphenyls (PCB) and polychlorinated dibenzodioxins (dioxins) |
| Carswell Air Force Base, Fort Worth (Texas, USA): Chlorinated solvents (NATO, 1998) | Novi Sad (Serbia) oil refinery (5 April - 2 May 1999): oil products, depleted uranium |
| Kleingötz near Günzburg, Germany, air base, ammunition testing: | Bor (Serbia) capacitors (15 May 1999): polychlorinated biphenyls (PCB) |

| Contaminated sites made in peace | Contaminated sites made in war (UNEP, 1999) |
|---|---|
| trinitrotoluol (TNT), heavy metals, polycyclic aromatic hydrocarbons (PAH), 1,1,1-trichloro-2,2-bis(4-chlorophenyl)ethane (DDT) (Heuschneider et al., 2000) | |

The requirement of sustainable development demands the prevention of contamination of soil. Furthermore, the requirement of sustainable development often can only be fulfilled if the contaminated sites are remediated. The way of cleaning-up contaminated soil is also relevant for sustainable development.

Since 1993, the German state Baden-Württemberg requires by law (VwV, 1993) the consideration of the environmental burdens of the remediation action itself. Six years later, the legislation for whole Germany (BBodSchV, 1999) followed Baden-Württemberg (table 2). In the mean time, Baden-Württemberg directed the development of a method for the evaluation the potential environmental impacts of soil remediation options (Volkwein 2000a, 2000b, 2000c; Volkwein et al., 1999, Bender et al. 1998, Volkwein et al. 1998). Finally in 1999, Baden-Württemberg released a software tool (LFU, 1999) "Umweltbilanzierung von Altlastensanierungsverfahren" ("Environmental balancing of soil remediation measures") which should be easily used by soil remediation planners in the planning process.

**Table 2. Foundation for looking at environmental burdens caused by soil remediation measures itself**

| Foundation of looking at environmental burdens caused by soil remediation measures itself | Example |
|---|---|
| International legislation or conventions | Rio Declaration, sustainability principle (UNEP, 1992) |
| National legislation | German legislation about soil remediation (BBodSchV, 1999) |
| Local legislation | Baden-Württemberg legislation about soil remediation (VwV, 1993) |
| International standards | Environmental management systems for organizations: continuous improvement of overall environmental performance of activities (ISO 14001:1996) |

Between 1996 and 2000 several international standards about environmental management emerged. The starting point is the standard ISO 14001:1996. ISO 14001 addresses to organizations. An environmental management system of an organization must include a commitment for a continuous improvement of the overall environmental performance of the activities of the organization. The overall environmental performance of an activity (service) can be measure with the management tool life cycle assessment (ISO 14040:1997, ISO 14041:1998, ISO 14042:2000, ISO 14043:2000). Due to the standardization, life cycle assessment is an internationally accepted tool. No other tool for the determination of the overall environmental performance of services has such detailed description of the methodology in ISO standards. Life cycle assessment is applied since 30 years under different names in industrial and other organizations (Hunt and Franklin, 1996). Life cycle assessment is the first choice for the evaluation of the overall environmental performance of a service.

The overall environmental performance of a site clean-up can be explored using life cycle assessment based tools. The decision support tool "Umweltbilanzierung von Altlastensanierungsverfahren" ("Environmental balancing of soil remediation measures") allows the fulfillment of the

- sustainable development principle for soil remediation and
- the organizational requirements of ISO 14001 for soil remediation organizations.

## 2 LIFE CYCLE ASSESSMENT FRAMEWORK

The life cycle assessment (LCA) method is still under development, but practitioners can refer to four international standards (ISO 14040:1997, ISO 14041:1998, ISO 14042:2000, ISO 14043:2000). According to the ISO standards, every life cycle assessment consists of four parts (Figure 1):

- goal and scope definition
- life cycle inventory
- life cycle impact assessment
- life cycle interpretation

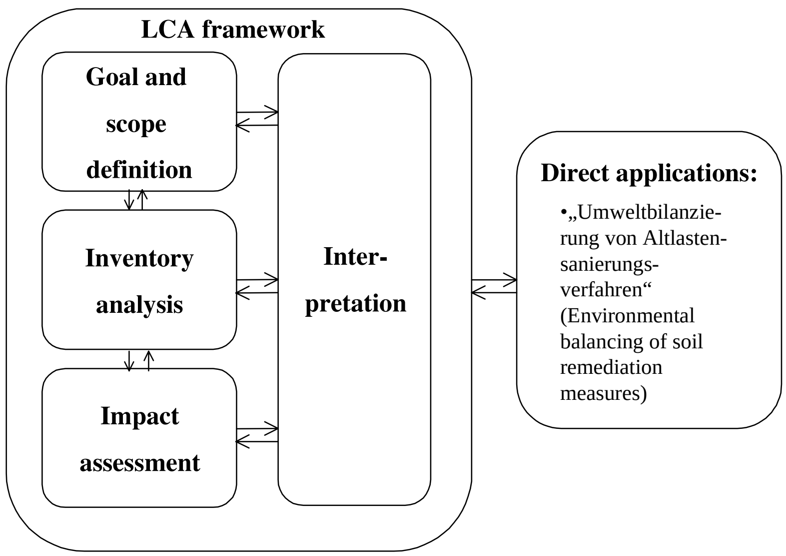


**Figure 1. Life cycle assessment (LCA) framework adapted from ISO 14040:1997 with special direct applications for soil remediation planning**

Life cycle assessment can analyse whole life cycles of services (products). The primary application of LCA is the analysis of the use phase of a product (service). Also important is the application in the manufacturing phase (design phase, eco-design). Another field for the application of LCA is the end of life analysis or end of pipe service analysis.

## 3 SOIL REMEDIATION PROCESSES

The soil remediation planning often starts with a historical reconnaissance of the contaminated site. A more detailed investigation of the pollutants, the amount of the pollutants and the distribution of the pollutants follows. Preliminary site remediation options are developed. At this point, the evaluation of the environmental burdens of the different site remediation options can start. The soil remediation planner can then use the result of this environmental evaluation together with the results of financial, legal, social and risk assessments to select the finally applied soil remediation option.

The future regular evaluation of the environmental burdens of the contaminated sites remediation has the following requirements:

- soil remediation planner should be able to make this evaluation himself
- low demand of time for this evaluation

Therefore, a tool for the evaluation of the environmental burdens should speak the "language" of the soil remediation planner. This language includes phrases like the following:

- mass of soil to be treated
- volume of soil to be treated
- transport distances for soil transport
- time of the clean-up
- type of the applied technologies for soil remediation

The tool for the evaluation of the environmental burdens should have predefined processes. Such a feature can support a quick application of the tool. The process names should be those which the soil remediation planner uses. The input data for the processes should be in the "language" of the soil remediation planner. Table 3 lists several processes that might be necessary to make a full soil remediation option.

**Table 3. Processes often used in soil remediation measures**

| General type of process | Group of processes | Processes, detailed for soil remediation option selection |
|---|---|---|
| Decontamination (clean-up) | Soil washing | Soil washing – mobile facility |
| | | Soil washing – semi-mobile facility |
| | | Soil washing – stationary facility |
| | Microbiological soil treatment | Microbiological soil treatment – turning bed |
| | | Microbiological soil treatment - rotting/composting |
| | | Microbiological soil treatment – reactor |
| | | Microbiological soil treatment – near to the surface zone in-situ |
| | Thermal treatment | Thermal treatment – Herne |
| | | Thermal treatment – Deutzen |
| | | Vacuum distillation |
| | Pneumatic tech. | Pneumatic techniques |
| | Groundwater treatment in-situ | Microbiological groundwater treatment in-situ |
| | | Reactive walls |
| Ensuring technologies | Immobilization | Immobilization |
| | Sealing walls, leak proof walls | Sheet-pile wall |
| | | Narrow wall |
| | | High-pressure injection wall |
| | Surface sealing | Capillary break |
| | | Surface covering |
| Secondary technologies | Civil engineering | Asphalt covering |
| | | Foundation, floor plate |
| | | Consolidating, compacting |
| | | Material consumption - processed earth materials |
| | | Material consumption – plastics and concrete |
| | | Material transport on-site |
| | | Distribution with bulldozer |
| | | Wells |

| General type of process | Group of processes | Processes, detailed for soil remediation option selection |
|---|---|---|
| | | Excavation work |
| | | Soil treatment: sieving, crushing |
| | Waste air cleaning | Adsorptive waste air cleaning |
| | | Catalytic waste air cleaning |
| | | Biological waste air cleaning |
| | Ground-water cleaning | Extraction of ground-water |
| | | Ground-water cleaning – stripping |
| | | Ground-water cleaning – sedimentation |
| | | Ground-water cleaning – precipitation, flocculation |
| | | Ground-water cleaning – chemical oxidation |
| | | Ground-water cleaning – adsorption |
| | | Ground-water cleaning – ion exchange |
| | | Ground-water cleaning – dewatering |
| | Transport | Mobilization, demobilization |
| | | Soil transport street lorry |
| | | Soil transport river ship |
| | | Soil transport rail train |
| | | Transport of persons by car |

The processes listed in table 3 are some of the processes included in the software tool "Environmental balancing of soil remediation measures" (LFU, 1999). The software tool "Environmental balancing of soil remediation measures" links these process data to generic life cycle assessment data and to a life cycle impact assessment model. The calculation of the life cycle impact assessment is automated. Results of the life cycle impact assessment and the life cycle inventory are transformed to an easy to interprete disadvantage factor table. An example is given in the following section.

## 4 CASE STUDY “FORMER COMPANY REINIG IN SINSHEIM”

The example "former company Reinig in Sinsheim" includes the comparison of three remedial alternatives. The contaminated site of the former company Reinig in Sinsheim has an area of 20000 square meter. Mineral oil contaminates 530 cubic meter, polycyclic aromatics (PAH) 750 cubic meter, and chromium 530 cubic meter soil.

"On-site ensuring" means the excavation and on-site redumping of the contaminated soil. The second remedial option ("soil sealing") is the simple sealing of the surface by asphalt. The "decontamination" option requires the excavation and three different treatments. 75 $m^3$ of contaminated concrete is included in the “on-site ensuring” option, but not in the other two options “soil sealing” and “decontamination”. In the option “on-site ensuring”, only 50 % of the PAH contaminated soil is excavated. The other 50 % of the PAH contaminated soil is under the clamp of the redeposited contaminated soil.

The details of the environmental balancing of the case study "former company Reinig in Sinsheim" are described in LFU (1999) and Volkwein et al. (1999). The disadvantage factor table 4 shows one important result. A disadvantage factor 1 means that the parameter value for the remediation option is the lowest among the compared remediation options. The cumulative energy demand (one of several parameters) is for the "on-site ensuring" lower than for "soil sealing" and "decontamination". Therefore, the disadvantage factor for the cumulative energy demand of "on-site ensuring" is one. The "soil sealing" requires a 20 times higher cumulative energy demand than on-site ensuring.

**Table 4. Disadvantage factors for the case study "former company Reinig in Sinsheim"**

| Impact categories and energy and waste | On-site ensuring | Soil sealing | Decontamination |
|---|---|---|---|
| Cumulative energy demand | 1 | 20 | 4 |
| Waste total | 1 | 2 | 40 |
| Waste from contaminated site to landfill | | | ! |
| Fossil resources | 1 | 30 | 4 |
| Water | 1 | 5 | 5 |
| Land | 2 | 7 | 1 |
| Global warming | 1 | 5 | 5 |
| Acidification | 1 | 5 | 3 |
| Photo-oxidant formation | 1 | 20 | 4 |
| Toxicity air – remote emissions | 1 | 3 | 4 |
| Toxicity water | 1 | 30 | 4 |
| Toxicity soil | 1 | 30 | 4 |
| Odor – remote emissions | 1 | 5 | 3 |
| Toxicity air – near emissions | 1 | 1 | 1 |
| Odor – near emissions | 1 | 1 | 1 |
| Noise immission 60 dB(A) | 1 | 1 | 1 |
| Noise immission 66 dB(A) | ! | | |
| Sum of disadvantage factors | NOT ALLOWED | | |

A "!" indicates that the other options have a parameter value "0". Soil washing in the option "decontamination" results in a certain amount of waste from the contaminated site. The options "on-site ensuring" and "soil sealing" have no "waste from the contaminated site" (parameter value = 0). This is the reason for the disadvantage factor "!" for the "decontamination" option.

One among several conclusions of this case study is, that the option "soil sealing" is in all analyzed parameters in table 4 equal or worse than the "on-site ensuring" option. A more detailed discussion of the results can be found in Volkwein et al. (1999) and LFU (1999).

## 5 CONCLUSIONS

Life cycle assessment is in use for analyzing whole life cycles of services (products). The primary application of LCA is the analysis of the use phase of a product (service). Also important is the application in the manufacturing phase (design phase). Another field for the application of LCA is the end of life analysis or end of pipe service analysis. The remediation of contaminated sites is a end of pipe service (repairing service for upstream industrial processes).

A necessity exists for knowing the environmental burdens of remedial actions itself if the sustainable development principle is applied or if compliance with ISO 14001 is desired. Life cycle assessment is the tool with the biggest international acceptance for evaluating environmental burdens of services (products). There are 30 years of industrial experience with life cycle assessment. There are three years of experience with an international standard about the basics of life cycle assessment (ISO 14040:1997). There is one year of experience with a publicly available software tool based on life cycle assessment. A state-of-the-art soil remediation tool-box shall include life cycle assessment based tools.

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# APPROACHES TO DECISION SUPPORT IN THE CONTEXT OF SUSTAINABLE DEVELOPMENT

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## ABSTRACT

Decisions on the management of risks from contaminated land and groundwater have much in common with many modern environmental decisions. The desire to integrate technical, socio-political and economic factors during risk management has resulted in the development of decision "frameworks" that allow an holistic approach within a context of sustainable development[1]. The application of integrated decision-making is in its relative infancy, however, and only recently have practitioners in contaminated land management considered its use. Here, we explore some of the decision tools that are available and, in the context of contaminated land remediation, explore the practical challenges with respect to integrated decision-making. Our aim is to set out some of the support tools that might be applied to contaminated site remediation, particularly at the site level.

## INTRODUCTION

Environmental decision-makers have at their disposal a vast array of support tools that have been developed over the last 30 years[2]. These tools are typically applied to assist with screening environmental impacts, for the assessment of risk / benefit trade-offs, for engaging a wider stakeholder community within decision-making processes and to the integration of technical, socio-political and economic factors that inform decisions on environmental management[3]. Decision support tools for environmental appraisal are being used increasingly at the policy, programme, plan and project level across a spectrum of environmental issues[4]. This presents opportunities for the cross-fertilisation of expertise and experience between disciplines and decision-making contexts (Table 1).

Over a similar period, policy makers and practitioners in contaminated land management have been developing decision-making frameworks of their own[5, 6], centering on well-established processes of risk assessment, risk management and risk communication (e.g., Figure 1). These frameworks embody many of the tools and component processes used by decision-makers elsewhere, including, but not restricted to:

- brainstorming techniques (for hazard identification and conceptual model development for example);
- scoping and screening (in qualitative risk assessment; in remedial technology selection);
- environmental fate and transport modelling (as a component of exposure assessment);
- sensitivity and uncertainty analysis (in quantitative risk assessment);
- economic appraisal of costs and benefit (in comparing remedial approaches, including the costs of 'do nothing' and the assessment of appropriate times for intervention)
- data analysis (in site investigation); and
- the collection of opinions and lay-perspectives on risk (for risk communication).

**Table 1. Synopsis of Decision Support Tools for Environmental Decision-Makers**

| Tool | Use | Environmental arena in which tool has been conventionally applied | Contaminated site context |
|---|---|---|---|
| Environmental risk assessment | Estimation of probability and consequence, usually for adverse environmental impacts at the site-specific level, but can be applied at policy level as strategic risk assessment (SRA). | Chemical product licensing, manufacture and use; production plant safety; environmental health protection; flood defence; liability auditing; contaminated land assessment; policy analysis; strategy setting. | Context well established; identification and analysis of hazards and potential environmental harm from contaminated sites; use of probabilistic techniques for dealing with uncertainties in exposure assessment; sensitivity analysis to assist in remedial technology selection. |
| Environmental (impact) assessment | Environmental, social and economic impacts of proposed developments; summarised in non-technical language; participatory approach advocated; can also be applied at the policy or sectoral level as strategic environmental assessment (SEA). | Environmental planning; siting of contentious installations (e.g., incinerators, landfills, tidal barrage); policy analysis; business sector analysis. | Siting of plant for the long-term treatment of residuals (e.g., secondary treatment of pumped groundwater); siting of containment facilities: scoping matrix approach for principal environment impacts. Strategic environmental assessment might extend to land regeneration programmes. |
| Social impact assessment | Assessment of the impacts of planned developments on the social fabric of communities, includes equity issues and impacts on social processes. | Not as yet conventionally applied in UK, more focused in USA and developing countries, but might provide useful basis for assessing the "social" part of sustainable development. | On more complex sites, SIA could be used to analyse the social context of a site or regeneration programme and to identify key pressures and benefits / possible constraints on remediation |
| Health Impact Assessment | Assessment of the health impacts of a development or process. | Recent call for it to be integrated into EIA – little distinction in practice from human health risk assessment within a planning context. Application in the context of air quality impact assessments for siting incinerators. | Nested within human health risk assessment |

**Table 1. (cont'd) Synopsis of Decision Support Tools for Environmental Decision-Makers**

| | | | |
|---|---|---|---|
| Cost-benefit analysis | Systematic and consistent appraisal and evaluation of economic and environmental costs and benefits of alternative projects, strategies and policies. | Appraisal of proposed investments in flood defence projects; BATNEEC and BPEO assessments of pollution control measures; policy appraisal and regulatory impact assessments. | Comparative assessment of risk reduction and costs for a variety of remedial technologies; assessing intervention times for groundwater plume remediation; at the strategic level may contribute to policy appraisal of statutory instruments and regulatory policies for contaminated sites. |
| Multi-criteria analysis (MCA) and multi-attribute techniques (MAT) | Integrated assessment of technical, social and economic impacts of alternative projects, strategies and policies. This incorporates monetisable/ quantifiable and non-monetisable/quantifiable impacts. | Assessment of risk management options; consistent appraisal of environmental benefits of water quality improvements by water industry so as to prioritise these measures in terms of their cost-effectiveness of securing environmental benefits. | Assessment of technical, socio-political and economic factors associated with a range of remedial options; integrating 'soft' data on risk perception and political risks with quantitative cost estimates and remediation efficiencies. |
| Environmental audit | Account of activities and production and resulting effects on environment; usually undertaken by an independent team with management support; the collation, analysis, interpretation and documentation of practices relevant to environmental requirements; checklist and Y/N guide approaches are common. | Improvement plans; setting insurance premiums; corporate environmental accounting and statements; liability (mergers, acquisitions and divestitures); regulatory compliance; efficiency of environmental management systems (EMS); due diligence; waste minimisation. | Well established for multi-site comparisons; focus is on qualitative risk assessment: source-pathway-receptor approach, worst-case and 'reasonable' worst case scenarios to drive remedial cost (liability) estimates. Considerable uncertainty in absence of site-specific information; multi-site comparisons undertaken by reference to source, receptor characteristics and regulatory pressure. |
| Life cycle analysis | Energy and mass balance from cradle to grave of products. | Manufacture; product replacement and substitution; supply and product chain management. | The design of sustainable remediation technologies and programmes; extension beyond simple capital and operational expenditure to issues of energy consumption and the secondary issues of residual products, off-gases and leachates and decommissioning, for example. See Volkwein *et al.*[9] |

**Table 1. (cont'd) Synopsis of Decision Support Tools for Environmental Decision-Makers**

| | | | |
|---|---|---|---|
| Sustainability appraisal | Developing area. Appraisal framework using sustainability objectives; potential application at all levels; flexible iterative process; indicators to monitor process; matrix/checklist approach. | Appraisal of regional planning guidance and regional strategies; policy and strategy appraisal. | Potential application to the appraisal of national or regional land regeneration programmes. Best viewed in terms of the integration of the above techniques. |
| Stakeholder analysis | Approach to analyzing the stakeholders involved in the decision process. Informal to formal approaches available; enables systematic consideration of all relevant parties and the relationships between those parties. Can provide an audit trail. | Carried out in an informal way within the EIA process. Associated more with social impact assessment advocated by stakeholder dialogue practitioners as a component of other decision-making processes. | Enables a systematic approach to understanding the range of stakeholders involved with a site / regeneration programme. Potential application to understanding the potential range of opinions and values that might be expressed regarding specific remediation options. |
| Engagement techniques[10] | Citizen's juries – Involves major stakeholders in the process of the identifying and appraising of options - lay people brought together to deliberate on an issue, call witnesses and come to a verdict.<br>Citizen's advisory groups - lay people bought together over a period of weeks to act as the voice of the community - can turn into a monitoring group once the decision has been made. | Applied in the context of hazardous and radioactive waste management. | Potential application for complex sites where a number of remediation options are possible and an informed public debate is desirable. |

**Figure 1. Framework for the Management of Contaminated Land (after DETR and Environment Agency, 2000[6])**

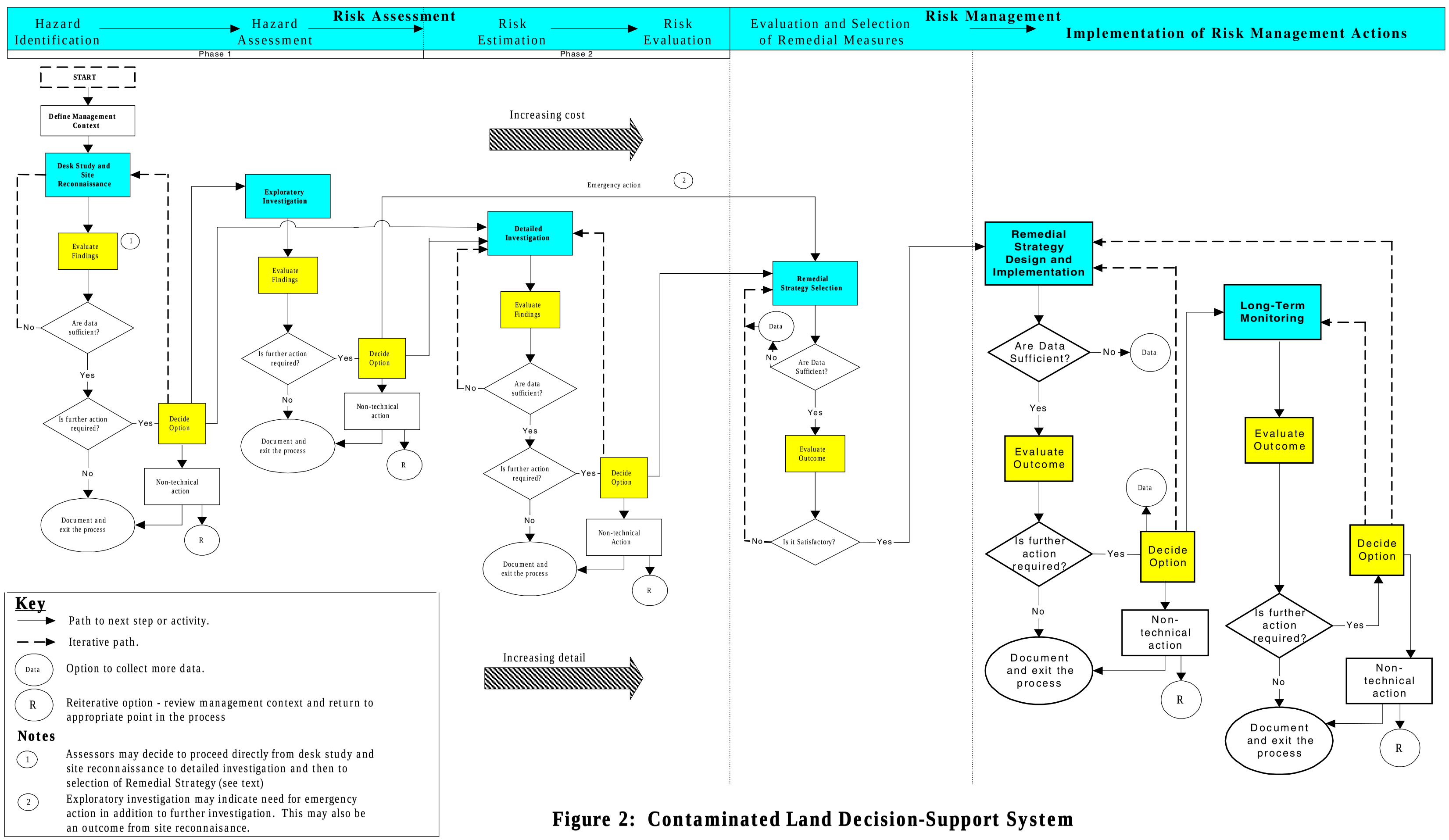


**Figure 2: Contaminated Land Decision-Support System**

Recent international reports and conference proceedings have pointed to a need to develop and adopt a broader range of decision support tools within the community of contaminated land practitioners[7,8]. Here we examine how some of the existing decision support tools might be applied to the challenges of contaminated land within a context of sustainable development.

## SUSTAINABLE DEVELOPMENT: ISSUES IN INTEGRATED DECISION-MAKING

A widely used international definition of sustainable development[11] is 'development which meets the needs of the present without compromising the ability of future generations to meet their own needs'. The UK strategy for sustainable development[12], which sets about establishing a better quality of life for present and future generations, establishes as its key objectives:

- social progress which recognises the need of everyone (equity within and among generations);
- effective protection of the environment (proactive approach to limiting environmental damage);
- prudent use of natural resources (clean and efficient use of non-renewable and renewable resources); and
- maintenance of high and stable levels of economic growth and employment (improved living standards for all; quality goods and services; education and skills).

This agenda gives weight to the integration of technical, socio-political and economic factors that inform decisions across Government, decisions that include, for example, about when and how to remediate contaminated sites. For practitioners, integration offers an opportunity to bring together appraisal and decision support tools historically used in isolation. Practical application, however, involves some considerable challenges, not least in resolving the differences in terminology, philosophy and output that are associated with individual tools (Table 2). The interface between the sustainable development agenda and the issue of land contamination is focussing on issues both relating to historic land contamination and those associated with the wider aspects of soil quality, including but not restricted to[13-15]:

- bringing land back into early beneficial use;
- the efficient use of national resources to tackle issues of highest risk at priority sites;
- reducing pressure on greenfield sites, thus conserving agricultural land and natural habitats;
- adoption of a suitable-for-use approach towards land remediation;
- prioritisation of remedial action so as to address the worst risks first in relation to the use of the land concerned;
- distribution of impacts on communities;
- the application of sustainable remediation technologies that conserve land and resources;
- the consideration of point and diffuse sources of soil pollution over the long term;
- the development and maintenance of new partnerships and fora among key stakeholders with agreements on a common research agenda; and
- the development of monitoring systems that allow early detection of adverse soil changes.

Addressing these issues requires a combination of policy, regulatory and technological responses that in themselves may require application of integrated decision support tools for a variety of policies, plans, programmes and projects. For example, the prioritisation of remedial measures in terms of which sites to act on first, the technology to be used and the appropriate times for intervention are increasingly subject to economic appraisal alongside issues of risk and technical feasibility[16]. As one contribution to the appraisal of sustainable remediation, economic appraisal brings new considerations to the decision-making process. We use this example below to illustrate some of the integration issues identified in Table 2. A similar discussion can be had for social and environmental components.

**Table 2. Integrating decision-support tools: some key challenges**

| Challenge | General commentary | Contaminated sites context |
|---|---|---|
| Identifying the full aspects of a problem | Time needs to be invested at the outset to determine all these aspects. For example, there may be a mix of traditional EIA issues, risk and potential social and economic impacts. Application of brainstorming and ‘risk register’ techniques. Wide consideration of stakeholder views. Key practical challenge is of how to include all diverse impacts, aspects and considerations of a problem in a systematic manner without ‘double-counting’. | Emphasis is usually on scoping out technical detail and conceptual model development, but often less emphasis on economic and social aspects of remedial programmes at the outset. Less the case for land regeneration subject to strategic assessment under the auspices of, for example, a local or regional plan. |
| Setting boundaries for the analysis | These need to be established and agreed both for consistency and for transparency and to make the appraisal practical. For example, there is a growing interest in EIA approaches encapsulating the entire life cycle of a project, ranging from the winning of raw materials to the final decommissioning and disposal stages. But there is a danger of becoming overwhelmed in excessive and unnecessary detail, so the analysis should concentrate on issues of significance to the environmental, economic and social impacts. | Tend to be established by regulatory context and owner/developer. Often technically, or financially driven with less emphasis on social issues. Greater consideration and involvement of the range of audiences earlier on can help avoid difficulties later with respect to disagreements over the scope of studies, the communication of risk assessment output and remedial technology selection. |
| Selecting individual techniques to potentially solve a problem | It is difficult to find off-the-peg techniques that are scientifically, professionally and socially acceptable. There is a dearth of guidance. At present a wide range of methods exist from formal frameworks such as Risk Assessment, EIA and CBA to deliberative approaches. Any single problem may require unique or novel approaches tailored to the case in question, or adaptation of an existing decision-making tool. This can take time in the short run, but can avoid significant problems at a later stage. | Most decision tools require tailoring to the specific circumstances because the context of application often requires an emphasis on certain aspects. An obvious example is the emphasis put on exposure assessment within the application of risk assessment for contaminated land. |
| Maintaining professional rigour whilst working in a multidiscipline fashion to integrate techniques | It is essential to apply rigorous professional standards in each discipline’s contribution, while still enabling their combination for the development of integrated techniques. | Clear specification of the impacts of remediation option across disciplines (technical, economic, social), without double counting, during appraisal. |

**Table 2. (cont'd) Integrating decision-support tools: some key challenges**

| | | |
|---|---|---|
| Linking tools and techniques together as appropriate | This is difficult because of the specific boundaries that surround techniques and the form in which each technique produces its findings. For example, risk assessment may report on the significance of a contaminant exceeding a threshold, whereas options appraisal techniques also need an analysis of risk reduction and residual risk to allow decisions to be made. Often it will be necessary to combine qualitative and quantitative information. Furthermore, models on which techniques are based may be incompatible. | Clearest example is of using risk assessment output to inform remedial design and selection. These processes still often viewed as distinct, however. There is a greater need to practice early iteration of risk management decisions following screening level risk assessments, so as to refine detailed risk assessment work. |
| Appropriate terminology to avoid misinterpretation of key terms and jargon | The above challenges are compounded by differences in the language and jargon customarily used by different disciplines and the interpretations attached to specific terms. | A common problem across the field of risk. Terminological differences can be overcome by focusing attention on the fundamental questions for which answers are sought. For example: hazard identification – what hazards are present on site? How might the consequences be realised? Who or what is at risk from these consequences? etc. |
| Non-dominance | No single technique or discipline must dominate the others or be perceived as dominating in reaching a final decision. | Historically, technical issues have dictated remedial selection. Structured, integrated analysis made explicit may result in challenges to the way that this is presented. |
| Consideration of increased public involvement | Current calls for increased public participation. There is considerable experience in EIA but less so in risk assessment, CBA or technology assessment. Structured and focused approaches are necessary, together with an examination of institutional structures and their capacity for meaningful public involvement. Monitoring and validation of these mechanisms is critical. | Increasing interest in risk assessment design and output. Mechanisms for participatory risk assessment not well established. Approach to date has been on technical risk assessment followed by 'risk communication' exercises to discuss output. US experience suggests limited success in this regard and many commentators now point to a need to apply engagement and participatory approaches. |
| Considering values | Deliberation is one way of uncovering people's values, but there are challenges as to how those values are incorporated meaningfully into decision-making and how representative groups are, such that deliberative analysis of small groups views may need to be supplemented by surveys of a larger sample of the relevant population. | Likely to have a complex range of values associated with a contaminated site. |
| Risk perceptions and lay epidemiology | Understanding the perspectives from which lay people address problems and valuing their local knowledge - challenge as to how local knowledge sits alongside expert knowledge. | Local effects attributed to sites by individuals / communities. Difficulties of establishing causality and reconciling reported observations alongside exposure assessments. |

**Table 2. (cont'd) Integrating decision-support tools: some key challenges**

| | | |
|---|---|---|
| Handling uncertainty | Recognition that in addition to uncertainty, there may be areas of ignorance where, in the presence of significant risk, the precautionary principle may be appropriate. To reflect the prevailing uncertainties results of appraisals need to be shown as ranges rather than discrete numbers. Uncertainty and sensitivity analysis can assist in highlighting the significance of ranges. | Integral to most environmental decision-making tools. Issues of blight and financial risk ensure this is problematic for most contaminated sites. Emphasis on quality assurance and control with respect to consulting advice, site investigation design and practice and remedial monitoring. |
| Using experts | The appraisal community is now taking on board participatory methods, combining scientists and non-experts. This raises important challenges and methods of eliciting and sharing technical information need to be developed and interrogated. | Use of experts at public inquiry especially with respect to remedial design and exposure assessments. Issues with respect to human health effects and toxicological data are difficult and tend to be addressed with reference to the deliberations of authoritative expert panels and committees. Application of expert elicitation techniques is common place in radioactive performance assessment for elicitation of receptor characteristics and representative 'futures'. |
| Deciding which timescale is appropriate | For example, sustainable development requires a longer-term perspective to be taken. There may be a need to undertake 'scenario-building' in parallel with a particular appraisal technique. | Issues of deciding when to intervene, for example, with respect to plume transport towards a public supply. Balancing times required for detailed assessment alongside plume advancement. Use of 'what-if' scenarios and futures to compare decisions. |
| Trading-off one option against another | There are particular challenges regarding how to present information on the trade-offs concerning risk management options. This also raises issues surrounding the choice of decision factors, the use of ranking, rating or scaling and, more controversially, weightings. | Challenges are particularly difficult where there is considerable uncertainty in the component parts of the decision. Issue of comparing quantitative and qualitative information is heightened. |
| Post-project analysis | It is imperative that the process is evaluated and lessons learned. | Improved project design and decision-making processes. |

## THE EXAMPLE OF ECONOMIC APPRAISAL

Economic appraisal is an important part of the appraisal of risk management options. It builds on the findings of the risk assessment and might typically involve the following generic steps:

(i). determine whether there are any existing binding statutory requirements or remedial objectives set by a higher authority (e.g., Government department such as DETR or the EC), already subject to their own economic appraisal. If so, then the economic appraisal by regulatory agencies should comprise examining how to achieve these objectives as cost-effectively as possible. It may be that the statutory requirements stipulate some caveats regarding the stringency with which Agencies should apply them such as ‘unless excessively costly’ or ‘unless there are overriding public interests’ (see EC’s Habitats Directive). In such cases, the analysis would have to consider whether such caveats apply;

(ii). where there are no existing binding requirements, it will be necessary to identify the alternative remediation and risk management approaches and strategies that are available. This should include issues of the timing of the remediation;

(iii). it is then necessary to appraise the environmental, economic and social impacts of these options to determine an appropriate remedial objective. This appraisal should include the costs of the options and their environmental impacts. The environmental impacts might include some impacts that could readily be assessed in monetary terms (e.g., impacts on local properties). There are likely to be other important intangible impacts that are difficult to value in monetary terms (eg impacts on human health and ecosystems). The appraisal should therefore set out fully as possible the level, nature and significance of these intangible impacts. This assessment should build on the scientific and risk assessments of the reductions in the likelihood, level and nature of the environmental impacts or risks that the remediation options could achieve;

(iv). once a remedial objective has been defined, then the appraisal should assess the cost-effectiveness of the available alternative remedial technologies for achieving it.

The purpose of an economic appraisal is not only to estimate the level of the costs and benefits of the options, but also to identify the key factors determining them so as to seek out and refine better options for all concerned with lower costs and greater environmental benefits. An economic appraisal brings the following essential considerations to the discussion and decision-making processes regarding risk management options.

(a) *Market Failure*. Environmental economics focuses on efficiently addressing market failures – which are external impacts that, in the absence of government action, private producers and consumers do not take into account. For example, market failure might covers cases whereby the costs to a developer for remediating a site exceed any increase in the value (gain) of the site as a result of the remediation so that, in the absence of any government action, the developer would not remediate the site (to a necessary standard).

(b) *Costs*. The economic appraisal assesses the costs of the options. These are often (in economics) called the ‘opportunity’ costs of the options because the options use resources that could be used for other beneficial opportunities or purposes.

(c) *Law of Diminishing marginal Returns.* This is the economist’s equivalent of the law of thermodynamics. It basically means that operators can face increasing constraints (eg extra resources and time required) as they reduce further the contaminants on a site and achieve extra environmental benefit. The law of diminishing returns has significant implications for the economic appraisal of remedial options because the trade offs between reducing the environmental damage from the contamination and the costs of this reduction become more significant as remediation progresses.

(d) *Valuation.* Finally economic appraisal entails the rigorous and consistent valuation of diverse impacts (apples and oranges) so that, as far as possible, they can be readily aggregated (without double counting) in terms of a single commensurate unit (usually money). This can then aid the comparison of the impacts of the options.

## PRACTICAL DECISION-MAKING

A recurrent theme of the application of structured decision support tools to complex decisions is that of practicality and the associated issues of cost and quality of the final decision. Alongside the current demands for transparency in decision-making are issues of cost-effectiveness that extend beyond the remediation technologies employed to the costs of the project cycle as a whole. For example, pragmatists may argue that the incremental costs associated with the environmental appraisal of remediation projects can not be justified when viewed in terms of the final outcome, which could have been arrived at through professional judgement without structured analysis[17]. One response to this is to view not only the cost-effectiveness but also the *uptake* of a decision by stakeholders (including the risk takers) as a critical indicator of a successful outcome. It is also important also not to regard an appraisal tool as an 'add on' and, therefore, a burden. Appraisal should be integral to the decision-making process and regarded as an iterative process.

Apart from the cost issue there is also the question of availability of an adequate skills base to carry out the appraisal. This is particularly the case for the application of specialised economic, social and environmental appraisals at the policy[18], plan and programme levels. Linkages between different levels of decision-making need further elucidation and development. In practice, many appraisals can be completed using inexpensive, but transparent screening techniques (*rapid appraisal*[3]) with more sophisticated tools (*technical appraisal*) being reserved for complex, higher priority projects. Screening is an accepted methodology in EIA and is becoming recognised (in the UK) as a means of targeting resources at the most deserving issues at more strategic levels. Checklist approaches, although with recognised limitations, have been used widely. The distinction between different ‘tiers’ of analysis is familiar to contaminated land practitioners in the application of risk assessment techniques. Furthermore, many appraisals will have core (fixed) and non-core (variable) aspects to their analysis[19, 20] and decision-makers can streamline their appraisal efforts by identifying core issues at a screening stage and focusing any additional effort on decision critical aspects of the analysis. This ‘tiered’ philosophy of approach is a common feature of most site investigations and familiar to practitioners in contaminated land assessment.

## CONCLUDING REMARKS

Risk management frameworks and their decision support tools have historically offered a systems approach to addressing environmental risk problems. The sustainable development agenda requires a more holistic approach, often with the integration of qualitative judgements alongside quantitative information[1]. At present, the debate amongst contaminated land professionals as to applicability of these tools has extended as far as the valuation of the intangible benefits of land remediation, but will need to extend to address explicitly the social impacts in order to embrace fully the objectives of sustainable development. Integrated decision support tools are required to assist this. In applying them however, it will be critical not to lose sight of the practicalities of application, the need for a transparency of approach alongside the defensibility of the technique and the over-riding objective, which is to make quality decisions on bringing contaminated land back into beneficial use.

## ACKNOWLEDGEMENTS

The authors gratefully acknowledge review comments received from Ian Martin (Environment Agency), Paul Bardos (r$^3$ Environmental Technology Limited) and Malcolm Lowe (DETR) during the preparation of this paper.

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# REVIEW OF DISCUSSIONS ABOUT DECISION SUPPORT ISSUES IN EUROPE AND NORTH AMERICA AT THE NATO/CCMS SPECIAL SESSION, AND OVERALL CONCLUSIONS

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## 1. INTRODUCTION

Environmental management of contaminated lands is a complex process requiring a wide variety of decisions encompassing different technical, social, and political questions. Decision support for contaminated land management is an emerging field. Currently, a consensus for the best approach for using decision support does not exist. A special session on decision support was conducted at the NATO/CCMS meeting held in Wiesbaden Germany in June 2000. The NATO/CCMS Pilot Study on Remedial Action Technologies For Contaminated Soil and Groundwater Phase 3 is a multi-national forum for the exchange of information on emerging remediation technologies and technology demonstration. The Pilot Study is an activity of NATO Committee on Challenges for Modern Society (Web site: http://www.nato.int/ccms/info.htm).

During the special session two guided discussion sessions were conducted and one set of questions to the conference participants was prepared. The discussion sections focused on obtaining information on the uses of decision support tools and the strengths and limitations of these tools. The questionnaire focused on gathering information on the use of decision support in the different countries participating in the meeting. This paper summarizes the findings of this information gathering exercise.

## 2. TECHNICAL BACKGROUND TO THE DECISION SUPPORT SPECIAL SESSION

Environmental management of contaminated lands is a complex process requiring a wide variety of decisions encompassing different technical, social, and political questions. The scope of contaminated land management problems range from minor contamination of a single site with a single contaminant, to multiple sources of different contaminants on a single site, to management of numerous contaminated sites in terms of sustainable development. The types of decisions that have to be made include:

- Identification / registration of problem sites
- Overarching decisions involving technical and social criteria (e.g., setting contaminated land policies)
- Setting management goals in a regional planning context (or corporate planning context)
- Prioritization of actions between sites
- Determining a course of action for a particular site
- Determinations within the individual steps of risk assessment / management for a particular site (e.g., how many samples are needed to support decisions on where to remediate).

The breadth in scope and sheer number of decisions required for contaminated land management has led to confusion as to what constitutes decision support. In this discussion decision support is taken to be: the *assistance for, substantiation and corroboration of, an act or result of deciding; typically this deciding will be a determination of an optimal or best approach* (Bardos *et al ibid*.). Although obvious, it is important to point out that decision support is NOT the same as making a decision. Decision support is the process of taking experience, data, and problem specific knowledge and the analysis and integration of this information to produce knowledge that assists the decision maker(s).

Decision support is one component of several in the decision making system. The others are: information/data, the management of that information/data, means of modeling / visualization of complicated information in a way that facilitates its interpretation, and gray matter. Gray matter means the human intellectual input that: sets out the technical approach to the decision making process; interprets decision making knowledge and reaches the decision. Figure 1 presents these components in a simple schematic. Figure 1 emphasizes the interdependence and feedback between different aspects of the problems through the two-way arrows. Eventually, the information is used in the decision making process.

An example of a decision making process might be the determination of which remedial options to use for a particular site. In this scenario, the problem begins with definition of a technical approach to the problem. Data are collected and managed. The data includes any information used to assess the problem including measurements of contamination and soil and groundwater properties, technical performance of remedial options, and costs of remedial options. The data are utilized directly for decision support in some cases. In most cases, the data are used in models that further analyze the data to provide information necessary for supporting decisions. The outputs from the modeling require interpretation on issues such as are the proper models and parameters being used for the analysis. The decision support variables also have to be interpreted in terms of their adequacy in supporting decisions (e.g., what uncertainties are there in the variables and will these uncertainties possibly lead to a different decision).

Figure 1 highlights the need for detailed thinking about the problem using gray-shaded boxes that use the term 'gray matter.' Decision support tools and techniques can supplement the decision process but cannot replace critical thinking, analysis, and judgment.

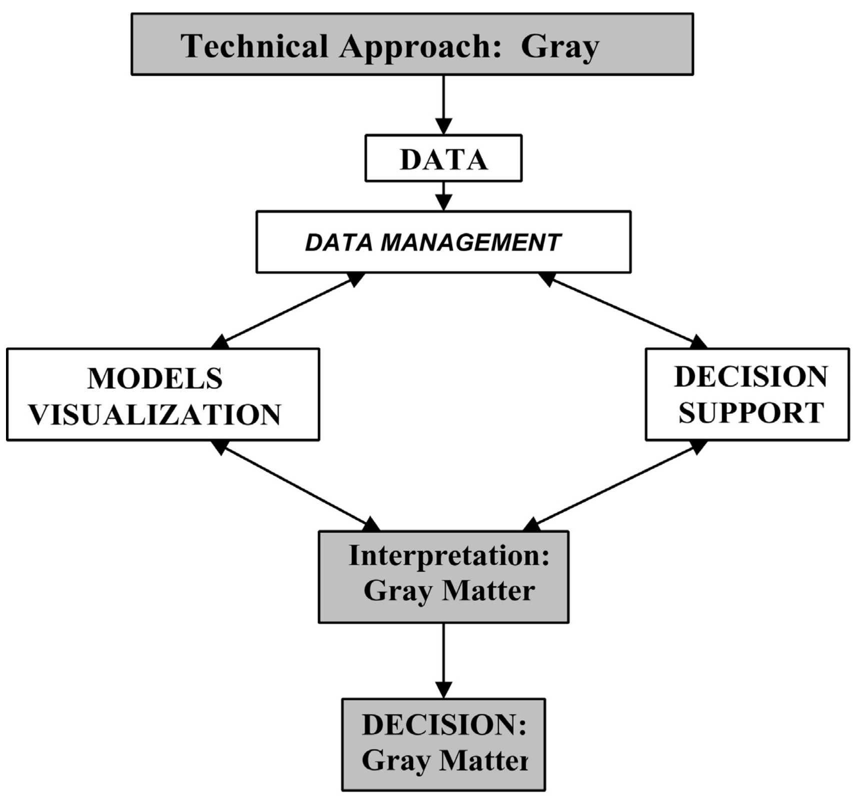


**Figure 1. Flow diagram of the decision making process.**

A number of tools are possible to support the decision maker. This discussion paper takes "decision support tool" to be *anything used as an instrument or apparatus in one's occupation or profession* (Bardos *et al., ibid.* ). Thus, a decision support tool (DST) is some kind of a product, which has the aim of supporting decision making.

In all cases contaminated land problems are resolved as a result of a series of inter-related decisions. A DST typically facilitates one or more of these decisions, as illustrated in Figure 2.

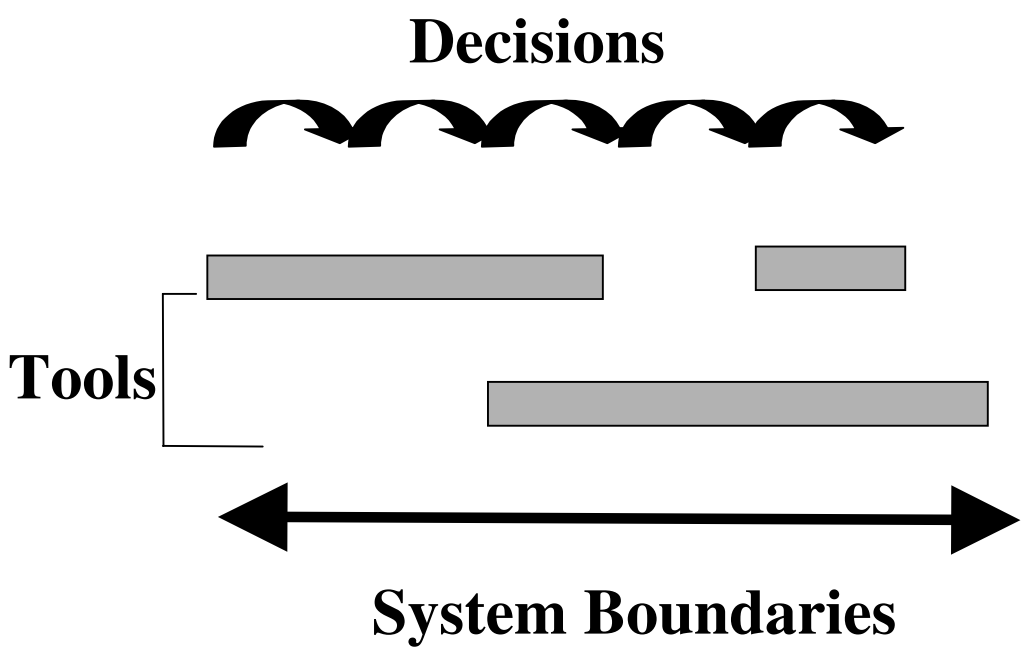


**Figure 2. Schematic representation of the relationship between decision tools and decision making**.

A DST can be written guidance on how to assemble and analyze information needed to support a decision (e.g., regulatory guidance on risk assessment, sustainable development, cost-benefit analysis, etc.). Alternatively, it can be a software tool that facilitates the data analysis and produces decision knowledge (e.g., costs, risks, etc.). In some cases, the software tools have codified the regulatory guidance to permit relatively easy and more consistent application of the guidance.

Figure 2 also shows that several decision support tools may be used in addressing contaminated land management. The entirety of the decision steps is the decision making system. No current single tool addresses the entire process. This is an important distinction, as many people would like a single tool (*a decision support system*) that could address all of the decisions. This would increase transparency (i.e., clarity of the process to all stakeholders) and reproducibility of the decision making process. However, because of the breadth and scope of decisions that need to be made this is not practical.

The system boundaries represent the constraints to addressing the problem and include regulations, time, money, and other limitations. Decision tools work within the system boundaries to provide information that supports the decisions. As shown in the figure, some tools will address a single decision (e.g., what region needs to be remediated to reduce human health risks to an acceptable level), while others will address multiple decision variables (e.g., selection of a remedial approach based on economic costs, protection of human health, technical feasibility of the approach, and stakeholder concerns).

In general, the use of decision support tools and techniques is an emerging field in contaminated land management. While some principles such as the use of human health risk assessment in decision making are widely accepted approaches for decision making, many areas such as ecological risk, multi-criteria analysis, life-cycle analysis, and financial risk analysis are only emerging as decision support tools. Even for human health risk assessment where guidance has been published in many countries, there is still much debate over the best approach (e.g., should specialized risk assessments be done for the young and old who may be more susceptible to exposure from contamination) to perform the analysis.

## 3. OUTLINE OF DISCUSSION SECTIONS

Two guided discussions took place during the special session, reviewing the papers presented (and included elsewhere in this report) and bringing to bear the delegates' own range of experiences from many countries. In addition, many delegates also provided written feedback over the course of the meeting. A list of delegates who attended is presented as an Annex to this report.

Ing Johan Van Veen led the first discussion section and focused on addressing the following questions
1) Are decision support tools useful?
2) How are DST being used?
3) What is the role of stakeholders in the decision process?
4) What common factors emerge between decision support tools?

Mr. Laurence Davidson led the second discussion section with the intent of determining the advantages and disadvantages of using DST.

The list of questions provided to the participants were:
1. How is DS considered in your country as a discipline or technique?
2. How is DS for remediation used in your country (e.g., types of applications, frequency of use? - Always, sometimes, almost never)?
3. In your view how well are information needs for decision making about remediation understood?
4. What is your view of the usefulness of Decision Support for selection of remedial options / risk management? Is DS used to support technology selection?

Participants from Austria, Belgium, Canada, the Czech Republic, Germany, Greece, Italy, Japan, the Netherlands, Norway, Switzerland, Turkey, the United Kingdom, and the United States supplied answers to these questions.

The following summarizes the results of the discussions and responses to the questions. In several cases, there was an overlap between the different discussions and questions. The following reports the findings as they occurred. No attempt was made to consolidate the different thoughts into a more concise manner.

## 4 FIRST DISCUSSION SECTION: APPLICATIONS OF DECISION SUPPORT TOOLS

### 4.1 ARE DECISION SUPPORT TOOLS USEFUL?

There was a consensus that DST can be useful not only in facilitating decision making, but also in helping to ensure consistency and transparency across decisions. However, this was strongly dependent on the DST approach. Unintelligent use of DST was perceived as counterproductive.

Written guidance on how to provide decision support knowledge was felt particularly useful. An example of these types of tools include written guidance on the approach and parameters to be used in human health risk assessment. Several people felt that these guidance types of tools were essential and in some cases adhering to the guidance is required by national laws.

There was less agreement on how useful software tools were in supporting the different decisions in the contaminated land management process. For example, most delegates agreed that human health risk assessment and cost-benefit software tools were valuable and widely used. Delegates could also see the usefulness of sample selection based on geostatistical analysis - yet these types of approaches are not widely used. However, while a number felt that DST could be useful for remedy selection, others felt that the use of software DST for remedy selection was not particularly useful, given the site-specific complexity of contamination problems and the absence of reliable general cost data.

A number of concerns were raised about the use of software DSTs in general. Often these tools use specific datasets and extensive assumptions. While the data and conceptual model are, in reality, the technical foundation of decision support, if it is unclear what the datasets and assumptions are, their relevance to the problem in question is unclear, and misuse of the tool a strong possibility. One delegate went further. He felt that even where a DST made transparent use of data, knowledge and assumptions, the mere availability of easy to use DST software presented risks of decision making being undertaken by inadequately skilled individuals.

These criticisms do not reflect a meeting consensus, but rather part of the range of views expressed. Other delegates felt that the way in which DST could improve the accessibility of data, analysis, and interpretation beyond those with expertise in the field was fundamentally a good thing. It allowed many stakeholders to actually "have" their stake in decision making. Those ultimately paying for or approving remediation decisions, and many of those wishing to influence decision making, are not necessarily contaminated land specialists.

However, it was suggested that the use of the tools still requires training and expertise in the different aspects of the decision making process and the analyses used by particular tools. The training should include guidance on the range of conditions over which the tool is applicable. This supports the notion that the tools can not be used to replace expertise, but only to enhance it.

The majority of delegates agreed with aspirations for decision support to help to make the decision making process transparent, documented, reproducible, (hopefully) robust and provide a coherent framework to explore the options available (Bardos *et al ibid*.). However, not all DST match up to these aspirations, and indeed the supporting datasets and assumptions of some DST are questionable for many applications.

## 4.2 WHAT IS THE ROLE OF THE STAKEHOLDERS IN THE DECISION PROCESS?

A stakeholder is any individual or group that has an interest in the particular contaminated land management problem. Stakeholders can include problem holders, environmental service providers, federal, state, and local regulators and public health officials, local businesses, citizens, and citizen groups. (PCCRARM, 1997; SNIFFER, 1999). The different perspectives held by stakeholders often leads to conflict in determining an approach to contaminated land management. In most countries, the problem holder or their consultant(s) analyzes the problem and suggests a remedy to the regulatory body. Typically, the public and other stakeholders are often informed of these recommendations at a later stage, often when decisions in principle have already been taken.

**Many delegates felt that early stakeholder involvement is beneficial both to avoid later delay and costs from subsequent arguments with unconsulted stakeholders and for reasons of open "governance".** Inclusivity in decision making is a part of sustainable development, which is an important policy driver in many countries. However, concern was expressed by several delegates that this inclusivity could lengthen the time taken to make a decision and in some cases be counterproductive. On the other hand, failure to include stakeholder viewpoints can often lead to more severe management problems later. Several suggested that stakeholders must be made part of the decision making process, but they should not be given control of the decision making process. Strong leadership and communication skills were identified as being crucial to dealing with all of the interested stakeholders, but maintaining an ability to actually make decisions.

## 4.3 HOW ARE DST BEING USED?

A number of applications of DST were mentioned during the discussions. Four major categories of use were identified.

- **The first is written guidance produced, for example, by regulatory bodies**. The guidance approach is used in a number of countries to enable a more consistent approach to contaminated land management.
- **The second category is use in identifying sites on a regional or organizational** (**e.g., corporate**) **basis and setting management / policy goals,** Activities supported include the identification of suspect sites, cataloguing suspect sites and setting broad "policy" objectives, which may be linked to a variety of spatial planning considerations, for example zoning of development and regional economic policy such as attracting inward investment**.**
- **The third category is the use of DST for prioritization among different sites within a single area of responsibility**. This activity is necessary where a number of suspect sites have been identified. Resources are not available to treat all simultaneously so the most urgent must be treated first.
- **The fourth category, which is the most commonly recognized application, is use of DST for specific tasks at a single site**. Examples of these type of approaches include analysis of human health risks, remedy selection, site characterization, and cost-benefit analysis. In most applications, a single decision criterion is evaluated. However, use of multi-criteria analysis (MCA) and life cycle analysis (LCA) approaches are often found.

Other important findings from the discussion were:

- Human health risk tools are the most widely used of any DST.
- For the most part, implementation of the tools is in the hands of the consultants and other technical specialists. Regulatory staff use them to a much lesser extent and the public and other stakeholders rarely use DST.
- When DST are used they tend to be only a small part of the decision process.

## 4.4 WHAT ARE THE COMMON FACTORS FOR DECISION SUPPORT?

Many decisions are required for contaminated land management. The decisions range from site and problem-specific questions that are largely based on technical and economic concerns (e.g., what is the best remedy to clean the site) to national questions that are largely based on societal concerns (e.g., prioritization of resources for the management of contaminated land to permit sustainable development). Although the emphasis on the decision variables may differ between different problems, they are interrelated. Site-specific problems can be influenced by societal concerns (e.g., neighbors may object to a technically viable solution such as incineration of wastes because they are concerned over airborne releases).

**Decision support tools integrate data and report results in terms of a simplified but representative decision information**. For example, assume that human health risk is one decision parameter for deciding if monitored natural attenuation is acceptable, or if a more aggressive remediation scheme is required. Many software programs predict the groundwater flow path and rate. While this information is required to analyze a contaminated aquifer, it alone does not address the consequence of the contamination and, hence, it is not a decision support tool. A decision support tool would take the information from the groundwater flow simulation and integrate it with information on the source strength and duration, contaminant transport processes (for example, removal by biodegradation), and exposure pathways and parameters (e.g., receptor location and use of contaminated water) to estimate human health risks over time.

**Stakeholder involvement is an important aspect of the decision process and helps to achieve a solution for contaminated land management that is acceptable to all**. Stakeholders may not always agree on an approach for contaminated land management. In this case, the regulators are often the mediators between the different stakeholders.

Risk management decision support tools are the most commonly used decision support tools. A number of delegates also identified cost-benefit decision support tools as having widespread application.

## 5. SECOND DISCUSSION SECTION: ADVANTAGES AND DISADVANTAGES OF DST AND GENERAL ISSUES ARISING FROM THEIR USE

### 5.1 WHAT ARE THE ADVANTAGES OF USING DECISION SUPPORT TOOLS?

The major advantage of using *appropriate* DST's is in helping to ensure the decision making process is robust, consistent, transparent and reproducible. Specific advantages of DST include:

- DSTs provide a method to analyze multiple scenarios. Consideration of a range of scenarios can increase the confidence when making a decision.
- DST can be used to optimize contaminated land management (leading to lower costs).
- Some DSTs can incorporate uncertainties into the decision framework. Decisions in contaminated land management are always made with some degree of uncertainty. Addressing this directly can enhance the decision making process. For example, DST can estimate the volume and costs of remediation required as a function of the degree of certainty in achieving human health risk goals (Stewart, 2000) or financial risks (Finnamore, 2000). This permits the decision to be based on the problem holder's aversion to failure.
- DSTs can provide means to document all parameters and assumptions used in the analysis for a particular decision (see subsequent discussion of data management systems).
- DST can improve communication between various stakeholder groups.
- DST can be used as an educational tool. For example, the effects of changing parameters on the decision variable can be demonstrated.
- DST can improve the transparency of the process through documenting assumptions and explaining the approach used to reach a decision.

### 5.2 WHAT ARE THE DISADVANTAGES TO USING DST?

- Gaining acceptability of the tool with all stakeholders is often difficult. It takes time and effort to educate other stakeholders on the use of a tool. If the tool is perceived to be a 'black box' stakeholders not involved in the application of the tool will not trust the results.
- A common approach to DST is to provide output in the form of a single set of decision variables, and in some cases a single variable or index. In reporting only the decision variable the rationale behind its algorithms, supporting data and assumptions may not be understood. The effect of this reporting approach may be to perpetuate a lack of trust of the analysis, which may be viewed as "black box" information. This is likely to be a particular problem where DST are used or interpreted by "non-experts". It also flags the need for clarity and good supporting information on the part of the system designer AND user.
- Decision support tools must be maintained to keep current. For example, for remedial options as new cost data are obtained they must be incorporated into the appropriate database for use in the analysis. In addition, human health risk decision support tools often have a database for risk parameters. These parameters are continually being updated to reflect the latest scientific findings.

- Garbage In – Garbage Out. A decision support tool is only as good as the data and assumptions used to perform the analysis. The assumptions include not only those used to develop the DST, but also those used in the conceptual model of how to represent the problem. Therefore, the analyst should be trained in the use of the tool and in the approach to represent the contamination problem. (See also Section 4.1).

## 5.3 WHAT ARE THE ISSUES IN THE USE OF DST?

During the discussion it became apparent that there were many issues that could not be claimed to be an advantage or disadvantage. For example, ease of use of the decision support tools was cited as an issue. Many people wanted tools that were easy to use, while others were concerned that without proper training the easy to use tools could be prone to misuse. For this reason, a third category, issues in using DST was added and the following issues identified.

- The use of many types of DSTs is in its infancy. In general, DSTs need to gain acceptance from all of the stakeholders, provide training on how to effectively use them and guidance on when they would be useful.
- The value added by using DSTs needs to be demonstrated. Purchasing a DST, learning how to properly operate a DST and getting other stakeholders to agree that the DST is appropriate for the problem can be expensive and time consuming. If all of this work does not lead to a better decision or more efficient process to reach the decision, use of the DST could be considered inappropriate. Anecdotal evidence was presented at the meeting indicating that in one case, use of a DST saved several million dollars on the remediation project. Situations like this need to be thoroughly documented and subjected to independent peer review.
- Contaminated land management requires good data management practice. It was suggested that a data management system is not a DST but it is an adjunct that supports the quality of DST analysis. As such, the data management system should be independent of individual DST or visualization tools. An ideal situation might be where a single data management system was used both to store basic data from its various sources and the interpretation of that data provided by visualization tools and DST. Indeed the data management package might be handed on across organizations on a CD-ROM to ensure that source and interpreted data is kept secure and well referenced. Providing everyone with the same data will allow independent analysis by other stakeholders using the same data. Maintaining a centralized data management system can also lead to better quality control of the data as all changes to the database will go through the data administrator. This will help insure that all data analyses will be performed with a common data set.
- There are gaps between the latest developments in decision theory and their implementation in DST. This is to be expected because the development of the theory generally precedes the implementation in DST. However, it highlights the need to continually maintain and update the DST, as new information becomes available.
- Validation/Verification of a DST is required, but difficult to perform. Validation refers to the demonstration that the DST performs as expected. Validation can be achieved by comparison of DST results with known solutions or with results from other accepted DST. Verification refers to the demonstration that the DST can accurately predict the behavior of the system. Due to the natural variability in contaminated land problems, lack of data, and the need for simplifying assumptions to represent the actual conditions it is generally not possible to verify the DST.
- DSTs are supposed to enhance transparency of the decision process. However, their development requires highly specialized knowledge and skills. For example, DST may implement state-of-the-art models for any or all of the following: geostatistics, subsurface flow and transport, human health risk assessment, ecological risk assessment, economic analysis, and decision theory. This highlights the previously identified need to educate and train stakeholders in the use of DST and the limitations in their use.

- The results from using DST may receive unwarranted credibility through the cloak of scientific rigor. The concern expressed was that if a well-accepted DST is used in the analysis, people will blindly accept the results without critically analyzing the assumptions and parameters. This highlights the need to remember that although the DST may be quite sophisticated in its analysis techniques it is just a tool. The decision process should still be based on thinking.

## 5.4 THE IMPORTANCE OF DATA MANAGEMENT

Decision support can be greatly improved through the use of data management tools that store the information electronically and permit its use by all stakeholders. A concern was expressed by some of the participants that if each DST had its own dataset this could lead to inconsistencies. Proper data management would remove this problem and can lead to improved quality control of data. Ideally, the data management system would contain all of the data related to the contaminated land management problem and be the sole source of data for decision support analyses. The different DSTs would access the database and extract the data needed for their analysis. Use of a centralized data management system would help improve consistency.

## 5.5 WHAT ARE THE ISSUES IN MULTI-CRITERIA ANALYSIS (MCA)?

Multi-criteria analysis is a well-established technique for optimizing decision making, however, use of MCA for decision support of contaminated land management is an emerging technique. In MCA, several alternatives are ranked against a list of criteria. These criteria can include costs, human and ecological risk reduction, societal values for the benefits of remediation, technical feasibility, and so on. From the preceding example, it is clear that each of these criteria will have different measurement scales and may rely on subjective judgement. Each alternative is evaluated against each criterion and given a score. The scores are then normalized to a single scale. Often economic cost is used for the scale. Using the normalized score, each criterion is given a weight to reflect its relative importance to the decision. For example, meeting societal values may be given a weight of 0.3, while meeting ecological values may be given a weight of 0.1. Then, for each alternative, the individual scores for meeting each criterion are multiplied by the weight for the criterion and a total score is obtained. The total scores for each alternative are then ranked to support the decision on selection of an alternative. As MCA is an emerging practice in this field, there is little guidance on how to score the different criteria, normalize to a single scale or select the weights applied to each criterion. This has led to the following questions for the use of MCA.

- Does it make sense to normalize all criteria to a single scale? Often everything is assigned a so-called monetary value. Is this the best choice?
- What is the best way to integrate more subjective data (e.g., societal values) with more technical data (e.g., costs or risks)?
- What is the basis for obtaining the criteria weighting factors? Optimally, they would be obtained by consensus among all of the stakeholders.
- How is transparency in the decision process maintained when weights and scoring are subjective?
- Is the process rigorous and robust when using subjective normalization and weighting?

It is clear that there are major concerns about the process of quantifying subjective data and comparison of dissimilar criteria. In order for MCA to become an important tool for contaminated land management, these issues will have to be addressed and general guidance on acceptable approaches is needed.

# 6. RESPONSES TO THE QUESTIONNAIRE

## 6.1 HOW IS DECISION SUPPORT USED IN YOUR COUNTRY?

In general, three categories of response to this question were obtained: a) not used at all; b) used in the form of guidance for best practices; or c) used for site-specific problems. In some countries, DS is not widely used. In most countries, DS in the form of regulatory guidance is frequently used and its application is required by some nations. When DS is being used, human health risk assessment and cost-benefit analysis were the most frequent applications. Multi-criteria analysis and ecological risk assessment are emerging uses for DS. LCA is being used on a limited basis for special problems. All respondents considered DS to be a technique rather than a separate discipline.

The following example applications were supplied in the responses:

- Regulatory guidance for conducting human health risk assessment or best practices for remediation.
- Prioritization of projects for obtaining state funding, and for social and land-use planning;
- Data management,
- Human and ecological risk assessment,
- As a communication tool for the spatial context for risk and through visualization of data,
- As a method to insure uniform application of regulations,
- To support selection of monitored natural attenuation as a risk management strategy,
- Optimization of remedial technology operation parameters to minimize costs.

## 6.2 HOW WELL ARE INFORMATION NEEDS FOR DS UNDERSTOOD?

There was a range of perceptions on this issue. Some people believed that information needs were well understood, while most did not. Most people felt that the needs were understood at the thematic level (i.e., contamination data, risk data, etc.), but not at the working level (amount of data required to make a defensible decision). Most agreed that the information needs were well understood by specialists and researchers, less understood by project management and regulators and not understood by stakeholders that are not involved in the analysis process. A few responses identified the following issues in information needs.

- Several areas of science are not well understood. Improved understanding could lead to better decision-making. Areas identified include long-term performance and cost data for remedial techniques, better understanding of subsurface flow and transport, and toxicology data.
- For MCA, using subjective criteria such as the value of remediation to society, approaches to quantify the value in monetary terms are needed.
- Data quality needs are not well understood. The impact of natural variability and uncertainties in the data on the decision need to be addressed.

One respondent pointed out that the challenge for decision support tools is to simplify the systems so that data needs are reasonable in terms of the number of parameters and the cost to collect the data. The simplifications have to be balanced against the loss of technical accuracy in the results (i.e., does the loss of technical accuracy and, therefore, increased uncertainty impact the decision?). Accuracy is only one of several required attributes for decision information. The overarching question being asked is how to best manage the contaminated land given the problem constraints. For example, in the UK the emphasis is now on data quality that is fit for purpose – in some circumstances this may imply that a fixed budget is spent on more information but of lower (but adequate) quality.

## 6.3 WHAT IS YOUR VIEW OF THE USEFULNESS OF DECISION SUPPORT FOR SELECTION OF REMEDIAL OPTIONS / RISK MANAGEMENT? IS DS USED TO SUPPORT TECHNOLOGY SELECTION?

Many respondents felt that DS was useful for initial screening in the selection of remedial options. A few respondents felt that it was also useful in the final selection of a remedy. Those that did not feel DS was useful for final remedy selection indicated that the uncertainties in the cost and performance data were too high for new and emerging remedial technologies to permit use of decision support tools. Most respondents agreed that decision support is useful for risk management. In many countries, guidance on risk assessment is available, and risk assessment is routinely used.

Many respondents generalized the question to express how decision support was most useful in their country. Most respondents felt that decision support was very useful in the form of regulatory guidance to obtain a consistent analysis framework. This helped set the stage for dealing with the different stakeholders in a fair and consistent manner. Other advantages cited for decision support included:

- Improved communication with stakeholders. Visualization of data was acknowledged as an important method of communication.
- Better management, integration and use of data. The use of an overarching data management system that managed the data for all decision support tools can improve quality control and permit greater access to the data.
- Ability to determine key processes and parameters that impact the decision.
- Better transparency to the decision process.

## 7. CONCLUSIONS AND FUTURE DIRECTIONS

Many decisions are required for contaminated land management. The decisions range from site and problem-specific questions that are largely based on technical and economic concerns (e.g., what is the best remedy to clean the site) to national questions that are largely based on societal concerns (e.g., prioritization of resources for the management of contaminated land to permit sustainable development). Although the emphasis on the decision variables may differ between different problems, they are interrelated. Site-specific problems can be influenced by societal concerns (e.g., neighbors may object to a technically viable solution such as incineration of wastes because they are concerned over airborne releases).

Decision Support involves integration of expertise and data, followed by analysis and interpretation of the results to produce outcomes in terms of decision variables (health risk, cost, suitability, etc.). For example, assume that human health risk is one decision parameter for deciding if monitored natural attenuation is acceptable, or if a more aggressive remediation scheme is required. Many software programs predict the groundwater flow path and rate. While this information is required to analyze a contaminated aquifer, it alone does not address the consequence of the contamination and, hence, it is not a decision support tool. A decision support tool would take the information from the groundwater flow simulation and integrate it with information on the source strength and duration, contaminant transport processes (for example, removal by biodegradation), and exposure pathways and parameters (e.g., receptor location and use of contaminated water) to estimate human health risks over time.

The decision support can be in the form of guidance that provides a framework for performing the analysis or software that has codified the expertise to allow more rapid analysis by many. The magnitude and similarity between contaminated land management problems has led to development of several computer software DSTs to address different aspects of the problem (site characterization, cost-benefit, risks, sustainable development, etc.).

Regulatory guidance is the most widely used type of decision support. In several countries, adherence to the guidance is required or strongly recommended. For software based DSTs, human health risk assessment and cost-benefit are the most commonly used. Ecological risk assessment and multi-criteria analysis are starting to see more use.

Stakeholder involvement is an important aspect of the decision process and helps to achieve a solution for contaminated land management that is acceptable to all. Stakeholders may not always agree on an approach for contaminated land management. In this case, the regulators are the mediators between the different stakeholders. Effectively integrating the stakeholders into the decision process is a difficult task requiring strong leadership and good communication skills.

The strengths, limitations, and applications of DST have been identified and discussed in this paper. The major strengths identified were the ability to provide a consistent, reproducible process for decision making and the ability to enhance communication between different stakeholder groups. The major disadvantage in using DST was in gaining acceptability of the tool to all stakeholders. This can be a time consuming process. A secondary disadvantage that was cited involved concerns that making the tools easy to use could lead to their misuse. Careful review is required for all results that support a decision.

Decision support can be greatly improved through the use of data management tools that store the information electronically and permit its use by all stakeholders. A concern was expressed that if each DST had its own dataset this could lead to inconsistencies. Proper data management would remove this problem and lead to improved quality control of data and would help improve consistency.

A number of unresolved issues pertaining to the use of DST were identified. Based on these findings several areas for improvement were identified. Some of the more important areas requiring further development include:

- Improved methods for valuation of criteria and determination of weights for MCA approaches. This includes the need for improved methods and approaches for handling subjective (soft data). Work needs to be done to develop a consistent agreed upon approach to using MCA.
- Improved transparency for the concepts behind decision support to all stakeholders. Greater stakeholder involvement is needed to gain acceptance of DST.
- Improved transparency in the output from DST. Decision support tools often involve abstraction from multiple sources of data and involve complex technical analysis.
- Improved methods for verification of the performance of DST. This is especially true in computationally intensive areas that require extensive experience to use correctly and are often based on data sets that permit multiple interpretations. These areas include flow and transport calculations, geostatistical modeling and optimization of remedy performance.
- Improved methods for understanding the impacts of natural variability and uncertainty on the decision process. Some DST address the role of uncertainty in making a decision, but this is an emerging field that needs further development.
- Critical evaluation of the successes and failures in the use of DSTs. This evaluation would help to focus future development work.

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