Framework for Decision Support used in Contaminated Land Management in Europe and North America

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Abstract

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.

Key words: contaminated land management, decision-making, software, models, remedy selection, decision support systems

INTRODUCTION

This paper forms part of a report on decision support from a special session of The NATO/CCMS Pilot Study on the ‘Evaluation of Demonstrated and Emerging Technologies for the Treatment of Contaminated Land and Groundwater (Phase 3)’, Wiesbaden, Germany, May 2000.

The Pilot Study 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 (CCMS) (*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 (US EPA 1998*a*) and monitored natural attenuation (US EPA 1999).

This paper has been produced for the NATO/CCMS Pilot Study Special Session on Decision Support (June 2000). The session was organised by Brookhaven National Laboratory (USA) and r^3 Environmental Technology Ltd. (UK) on behalf of the US Environmental Protection Agency and the Environment Agency of England and Wales, respectively. It 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*). UK participation in CLARINET is supported by the Department of the Environment, Transport and the Regions.

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 (WG 2) 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.

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The CCMS was established by Council of NATO 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, and is under the direction of Dr Deniz Beten, CCMS Secretariat, NATO, Brussels. Further information about the work of the CCMS is available on *www.nato.int/ccms/info.htm*.

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 standardisation 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 rationalising 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 prioritising use of resources. Each has their 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 analysing the samples and the value of additional data in arriving at a more robust decision.
- Based on the initial site characterisation data, interpolation, extrapolation and other modelling 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 prioritising 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 manage-

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

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)? What risks may result to workers as part of the remediation effort? For affected aquifers: their use and importance How can the risks best be managed? What are the regulatory criteria? What are the success criteria for the proposed remediation? Fate of contaminants 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.)? How will remediation performance be measured? The availability and suitability of existing information for the site What time-scale is appropriate for remediation? What is the site availability for remediation works? What is the size of the site? What space is available for remediation operations? What are the current uses of the site? Ground conditions (materials, surface conditions, geology) Does the remediation need to cope with underground structures and/or work under buildings? Hydrogeology and groundwater monitoring Site access, security, services and facilities
Stakeholders' / third parties' views	What are the adjacent properties, who owns them and how are they affected? How will stakeholder communication be managed? What impact will the remediation have on site occupants and neighbours? 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)? Wider economic value Wider social value Use of resources, including land resources, for example in relation to the long-term use of the site and how this is to change
Costs	Capital and operating costs Balance of costs to benefits / cost-effectiveness Funding Restrictions: insurances, liabilities, securities

ment. 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*a*,*b*, 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.

1. Publications on this subject are forthcoming from CLARINET in the next 12 months and will be announced on its website: *www.clarinet.at*

2. Information on TechDirect is available at *www.clu-in.org*

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 standardised, 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 modelling, 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.

'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 though 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.

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 analyse 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

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; organised combination; method; a co-ordinated body of principles, facts, theories, doctrines etc.; a logical grouping; an organised combination of things working together performing a particular function; any complex and co-ordinated whole*

spent to support the decision on a course of action.

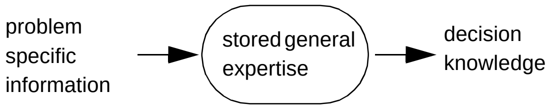

Figure 1. Illustration of decision support

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 level that is acceptable for residential use. For a series of contaminated sites, the objective may be to prioritise which sites to remediate first to minimise risks while maximising 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 behaviour. 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 favours 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 they do not always examine the underlying assumptions. A caveat applies to all computer-generated output; the output is only as good as the data and modelling assumptions used by the software.

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 analysed 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 ensure 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. 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 modelling techniques and software, is a step in the collection of information that precedes decision-mak-

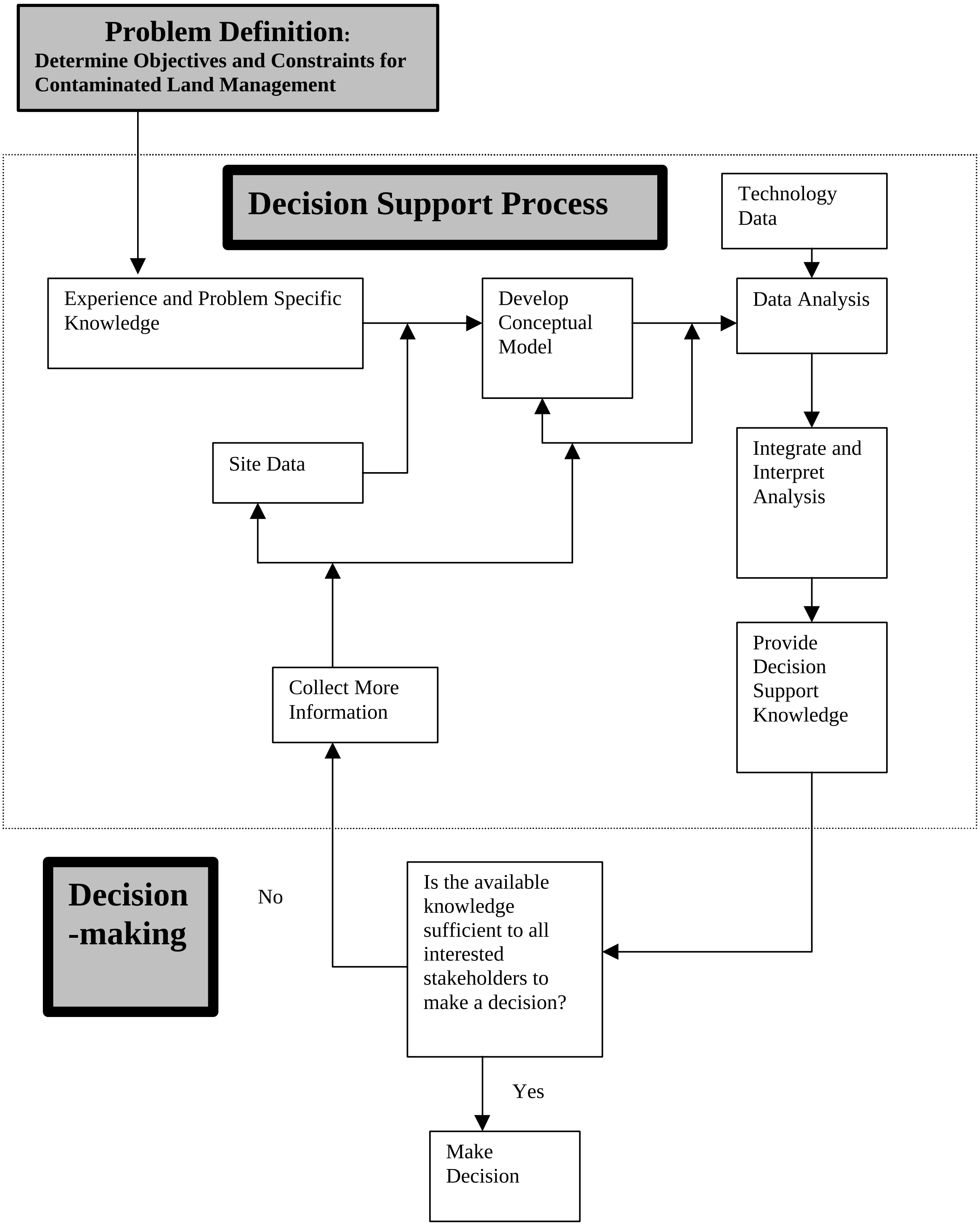

Figure 2. Flow chart containing the key steps in the decision support process

ing. 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 neighbours 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 emphasises 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.

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.

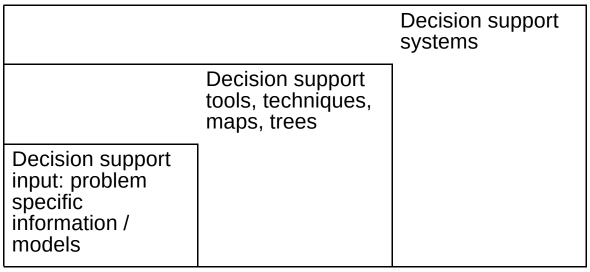

Figure 3. Decision support information, tools and systems

TYPES OF DECISION SUPPORT

Contaminated land management involves a series of decisions, as management of 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; prioritising 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,

Table 3. Categories for decision support tools

Problem solving role	Functional application	Analyses used	Nature of the product
Identification of problem sites Prioritisation Comparison of options Strategy development – policy – site specific	Problem identification Site investigation Risk assessment Risk management Aftercare Monitoring Evaluating wider impacts (environmental economic etc.) Sustainability appraisal	Risk assessment Cost benefit Life cycle Multi-criteria analysis	Written guidance Model procedure Software

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 a modified MCA approach)
6	Refining comparisons and testing sensitivity to changes in input values
7	Interpretation

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, or 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.

CATEGORIES OF DECISION SUPPORT

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

1. *The decision-making role of the approach*
   This describes the type of decision-making being supported, e.g. for managing a single site, or for prioritising a number of sites. This deals with the overarching decision being made at the site.
2. *Functional application, i.e. the contaminated land management application*
   This describes whether the decision support is for risk management, remediation, monitoring and aftercare, sustainable development, etc. and deals with the issues that must be addressed to support the overarching decision.
3. *The analytical techniques used in the decision support approach*
   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.
4. *The nature of the decision support product*
   This 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 summarised in Table 3.

In practice, many DSTs 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 risk based decision factors below). 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.

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 1995*a*,*b*).

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) 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.* 2000*b*).

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; US EPA 1995; US EPA 1998*b*). 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).

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 land must support multiple goals that are often conflicting. 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 characterisation or monitoring) are analysed 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 characterisation 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).

Overarching decision support *systems* include the ‘Model Procedures’, written guidance under development in the UK (DETR and Environment Agency). 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 analyse the data using detailed technical models, abstract and interpret the model output to address the technical questions, and present this information (often through visualisation techniques) for use by a non-technical audience (such as judge and jury) (Green and Delaney 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 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.

RISK-BASED DECISION FACTORS

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 (US EPA 1989; US EPA 1996*a*; US EPA 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 prioritised accordingly.

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

1. the source of contamination (e.g. a solvent spill, or buried materials on a redevelopment site);
2. 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);
3. the pathway (the route by which a receptor could be exposed to 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 with 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 characterisation of such a relationship, including, for example, delineation of the source, measurement/modelling of fate and transport processes along the pathway, and the potential effect and behaviour 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.

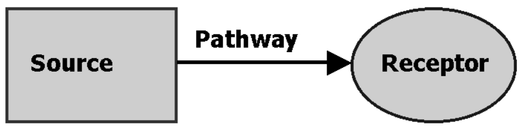

Figure 4. A pollutant linkage

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 (US EPA 1997; US EPA 2000) and how to manage ecological risks (US EPA 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.

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.

Technical suitability/feasibility

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 favoured solution or have different perceptions and expertise.

Stakeholders

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 neighbours (tenants, dwellers, visitors); advocacy organisations 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. 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 unit. 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 definition 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 greenfield 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. odours, dust, noise) associated with remedial options for a remote site may be less important than for one in a city centre. 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 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 cannot 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 US 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 clean-up 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 over-riding 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 project 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 incineration as a treatment option have been prevented because of stakeholder concerns.

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 exist 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 characterisation 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 programme (Sullivan 1999*a,b*; Sullivan 2000*a,b,c,d*).

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

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 industrialisation and industrial change have 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.

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 conceptualisation of the 'real world' into a construct that permits analysis using a computer. This conceptualisation process involves a number of assumptions. It is important for the models and assumptions to be thoroughly documented to permit an evaluation of the model's 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 realisations 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 visualisations. Software that is easy to use is more efficient at using the analyst's time.
Training and technical support	Are training and technical support available? Many of the DS tools require specialised expertise (i.e. flow and transport modelling, 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.

CONCLUSIONS

Contaminated land management is an important issue throughout Europe and the USA. The need for developing techniques and approaches to improve the decision-making process for reuse and/or remediation of contaminated land is widely recognised. 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 expertise, 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 (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, analyse 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 reuse. 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 a question of which 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 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.

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