Decision Support Systems for the Post-Emergency Management of Contaminated Territories

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Abstract

The work implemented within the framework of the project was directed towards understanding the conceptual basis for the organization of intervention strategies after the accident at the Chernobyl nuclear station. Based on the situation in regions of Belarus, Russia and Ukraine that suffered the consequences of the accident, this project was directed towards the provision of support for decision makers. The work will assist in the choice of proper strategies to protect the population from the effects of environmental contamination, taking into account the available resources. The experience gained, both of the problems of decision aiding in this context and their solution, will be of use in post-emergency planning for possible future accident situations.

At present there are several prototype computer systems which provide the following: access to a wide range of information gathered after the accident at the Chernobyl nuclear station in the CIS; support in complex evaluations of the post-accident situation for a wide range of parameters; analysis and forecast of how the situation may develop using mathematical models and algorithms; support in choosing strategies at each level of decision making taking into account the possibilities of applying a wide range of countermeasures; exploration of multifactor interdependence and the consequences of resource and other limits; the integration of experience in social and psychological factors into the decision making process.

Calculations made by the computer modules are based on actual data from contaminated territories, including structure of soils, age/sex structure of the population, and dietary habits. At present the models for the calculation of doses and radionuclide migration in soil are specific to the regions contaminated after the Chernobyl accident. They are based on a large amount of experimental data ranging from whole body measurements of the population to data about radionuclide transfer from soils to plants, milk, and meat.

A risk module has been developed which includes a database of demographic data on health protection for different territories, and which can calculate risks for any population structure. It can be used for risk estimation for different age groups in any region for which data is provided.

A module on indirect countermeasures has been developed to assist in the selection of countermeasures that will improve conditions for a population that inhabits a contaminated area, in a way that is distinct from a direct reduction in the effective contamination level of the

environment and its products. These types of countermeasure can be taken both as separate actions or in combination with direct countermeasures to increase the efficiency of the latter.

The tools and interfaces developed within JSP2 enable the decision maker to estimate consequences and analyze the post-emergency situation according to his own criteria and in a user-friendly manner. The available analyses include: forecast calculations (concerning the estimated contamination of agricultural products, the levels of doses in the local population, and the associated radiation risks); the identification of the critical factors that influence the health of the affected population; a simulation of human intervention taking into account the countermeasures chosen or a time ordered set of countermeasures; an estimation of the influence such factors as dose, risk, cost/benefit and time, etc. have on decisions. The results can be presented in the form of maps, diagrams, and tables.

In this paper, work carried out on the development of computer based decision support systems for the post-emergency management of contaminated territories is discussed, together with possibilities for further development of such systems.

Introduction

Following an accidental release of radionuclides to the environment, there may be a need for countermeasures to be implemented to protect the public. These countermeasures can be classified either as emergency or as longer term countermeasures, depending on their urgency of introduction and their duration. In general, emergency countermeasures are short term actions, such as sheltering, evacuation (for a few days) and the administration of stable iodine. Their primary role is to protect the public from exposures during the release and initial dispersion of the radionuclides. During the emergency phase of an accident, there will, in general, be insufficient time for many detailed measurements to be made or thorough evaluations of the impact of the accident to be undertaken. Therefore, emergency countermeasures are usually introduced according to pre-determined criteria, and based on rapid and approximate calculations. However, because such countermeasures are short term, the scale of any undesirable or unintended consequences is necessarily limited. Longer term countermeasures, by contrast, may continue for many years. Their purpose is to protect the public against continuing, relatively low level exposure from radionuclides in the environment. The risk from short term exposure to these environmental sources is unlikely to be serious: it is the cumulative risk from prolonged exposure which is considered unacceptable. Because such countermeasures may be in force for long periods, the consequences of non-optimal intervention may be very undesirable or costly. It is therefore of particular importance that the design and implementation of such countermeasures should be tailored to the exact post-accident situation taking into account the potential for long term adverse effects. Decisions on such countermeasures are therefore likely to require a large amount of detailed measurement and supporting information. The longer decision time available to work out the details of such countermeasures provides the opportunity to consider the information more fully than during the emergency phase. However, the difficulty is in assessing and synthesising this information, so that the best decision can be made on a reasonable timescale. This synthesis of large amounts of disparate information in the post-emergency phase of an accident is ideally suited to computer management. Within the Joint Study Project 2 (JSP2) of the EC/CIS collaborative programme recent computer developments have been explored in terms of their potential application to post-emergency management, and example models and modules developed. This is the subject of this paper.

The post-emergency phase of an accident is likely to be characterised by the emergence of a wealth of information from a wide variety of sources. For example, an increasing number of radiological measurements should become available, both those requested by the authorities and those made by independent groups. Widely varying opinions and expert advice are likely to be promulgated regarding the most likely future course of environmental contamination, exposures, health effects, and the possibilities and costs of countermeasures for averting these. Pressure groups may emerge to present the interests of particular population groups, and the affected populations will be subject to significant stress. Despite, or perhaps partly because of, the growing volumes of information, the situation will be full of uncertainty. It is likely that anomalies in the measurements and predictions will appear, due to a combination of error, misunderstanding and the sheer complexity of the environmental situation. Moreover, since exposure of the population to the contamination will partly be dependent on behaviour patterns, the prediction of the interaction between social-psychological factors and behaviours which can affect exposure is necessary, if countermeasures are to be evaluated. The emergence of pressure groups and the spread of opinions and advice will tend to require at least some protective decisions to be taken quickly, even though, from a solely radiological risk perspective, this would not be necessary. However, decision makers have a responsibility for considering the wider implications of their decisions: the need for equity between individuals and communities, the need for continuity (frequent changes in countermeasure policy is likely to increase stress and mistrust of the authorities) and the need to limit the commitment of resources to a level commensurate with the scale of the problem. Moreover, there are different levels of decision making required after an accident. At the highest level, a global policy is required, eg generic criteria for initiating the implementation of major classes of countermeasures, such as relocation. But in areas where such policies indicate that countermeasures are needed, the detailed implementation needs to be worked out, including timescales for implementation, practical methods, degree of involvement of those affected in planning the detail and so on. Different levels of decision require different types and amounts of information. One task of a computer based post-emergency support system would be to select the information relevant to each level of decision maker. All these issues are discussed in the paper.

Needs of the Decision Maker

A post-emergency computer decision support system should exist to meet the needs of the decision maker. It is important to recognise that the purpose of such a system is not to replace the decision maker but to facilitate his job by presenting what is known or can be predicted in a relevant and straightforward manner. As mentioned in the introduction, the post-emergency management of an accident is likely to involve a hierarchy of decision making, ranging from generic policy statements at a national level, down to specific local implementations of national policy in a settlement or at community level. Clearly, decision support should be tailored to meet the needs of particular types of decision and decision maker. Thus, a single system, with the inherent advantages of continuity and data sharing, may require several presentational forms if it is to try to meet all needs. However, whether a multifaceted single system or a series of independent systems, it is possible to identify factors and requirements that are common to most levels of a decision hierarchy. These are: the need to store large amounts of heterogeneous data, to keep this database up-to-date, and to facilitate the selective retrieval of these data and their presentation in a helpful form; the need to enable the consequences of possible protective strategies to be explored ('what-if' type questions); the need for possible strategies to be suggested, ranked, rejected; the need for a wide range of non-radiological (eg demographic, geographic, economic, regulatory, and social-psychological) data to be stored; the need for the system to incorporate a range of models/algorithms for interpreting data, and for the system to select the appropriate ones in response to a particular request; and the need for a flexible interface with the user, so that questions do not need to be posed in potentially obscure scientific terms. These common requirements are discussed below.

An intervention strategy may consist of a combination of one or more countermeasures, or no action. In order for such a strategy to be developed, it is necessary not only to evaluate the likely consequences of each individual countermeasure, but also the consequences of any interaction between countermeasures that may take place. The range of factors that need evaluation can be very large, although they will depend on the level and type of decision being made. Clearly, the prime purpose for introducing countermeasures is to reduce adverse health effects in the population. These health effects comprise both those resulting directly from exposure to the radionuclides released in the accident, and those resulting from increased stress caused either by the accident itself, or the subsequent accident response measures. For example, such factors could include: characteristics of the release or environment such as radionuclide transfer factors, initial deposition levels and soil types; geographic factors such as land use; and social psychological factors such as lifestyle and the likely level of compliance with official advice. In addition, all decisions would need to consider temporal and spatial aspects of the proposed strategy. For example, where the proposal is to implement a generic countermeasure such as relocation in areas where the average ground deposition level exceeds a specified criterion, the decision maker requires, amongst other things, information on the extent of areas contaminated above given levels, the practical constraints on timescales for introducing countermeasures (which in turn requires demographic data and knowledge of the spatial distribution of resources), and the possible reception areas for the relocated population. Moreover, where local decision makers need to interpret national policy for the local situation, it is important that they should have access to information on the legal framework within which they are operating. An important aspect of a computer decision support system is therefore the capacity to store large amounts and varieties of data which may be rapidly and flexibly retrieved within a spatial and temporal context.

There is another way in which temporal and spatial considerations influence decision making. Decision makers need advice on the harms and benefits of delaying a decision until additional information has been collected, compared with making the decision based on current knowledge. They also need information on the likely impact of a decision for one location on other locations, both in terms of economic interactions and in terms of social implications. Ideally, the computer system should support such questions as 'what benefit do I gain by postponing the implementation of countermeasures whilst I collect more data?' and 'if I do this in this settlement, what will be the effect on my options for other settlements?'. At one level this requires a sophisticated user interface, but, more importantly, it requires an intelligent and flexible synthesis of different types of information held within the system, and an ability to assess the overall uncertainty associated with this use of the data.

The above examples also illustrate the need for an interface that supports the decision makers' needs, by providing management options and guidance as opposed to a scientifically oriented tool providing descriptive and mechanistic analyses. The questions asked by decision makers need to be re-interpreted in order for them to be answered as a series of specific steps that can be carried out by a computer. The ideal support system will not require this decomposition to be done by the user, in order to ensure that it may be easily used by both local and high level decision makers and their advisors. The system should therefore decompose the more general questions into their constituent parts. This has implications, not only in terms of the interpretation of the primary question, but also in terms of the imposition of constraints on the scope of the analysis, eg in space, time, detail and accuracy, and hence the appropriate selection of models/algorithms and data. For example, a high level decision relating to the whole country requires only approximate measures of the consequences of adopting a given strategy. For this, simple empirical models or those designed to predict average consequences over a period of several years are the most appropriate, together with data aggregated over major geographical units. However, the local implementation of the strategy, eg the decision on how best to cultivate a particular field, given national constraints on maximum permissable radionuclide concentrations in foods, requires site specific models appropriate for that growing season, and data specific to that location.

Models Relevant to Post-Emergency Decision Support

The discussion of the needs of decision makers has indicated a need for a wide range of models and algorithms for processing radiological and other data in the post-emergency phase of an accident. These include models for interpolating between measured data, models for predicting into the future or into areas where there are no, or very limited, measurements, and techniques for combining model predictions/estimates and measurements. In addition, there is a need for models of varying degrees of complexity and precision, depending on the type of decision being taken, and the timescale on which it must be made.

Even in the very long term after an accident, measurement data will never be sufficient to define the full impact of an accident. It will always be necessary to interpolate between and extrapolate from measurements in both space and time. Where measurements are plentiful, the uncertainties introduced by appropriate procedures may be small. Where they are more sparse, it will be necessary to use models to supplement what can be deduced directly from the measurements. These models, which can be empirical or phenomenological, are required to estimate a wide variety of endpoints. Such endpoints include: environmental radionuclide concentrations, doses, risks, costs and effectiveness of countermeasures, costs and effectiveness of medical treatments, the social psychological response to countermeasures, the consequences of indirect countermeasures (ie those not directly addressing the radiation risk from the accident, but used to reduce other risks or to enhance the effectiveness of direct countermeasures). Any model should also include an estimate of the uncertainty associated with the result, both that arising from the data input to the model and that introduced by the model itself. Where a series of models are used, then these uncertainties need to be propagated through the sequence together with the model estimates.

Ideally, a computer decision support system should incorporate, for estimation of a given endpoint, models of differing complexity, scale of application and input data requirements. This is for two reasons. First, the amount and quality of data available to the system will vary depending on the data type, the area of interest and the time after the accident. The models or algorithms best suited to manipulate these data will therefore also vary in accordance with the available data. Second, the nature of the decision being taken will influence the type of model that is most appropriate, in terms of the precision, detail and scope required. The system should therefore hold information about the applicability of the models contained within it and select appropriate models based on the amount and quality of the available data and the type of question being asked.

Computer Techniques and Developments Relevant to Post-Emergency Decision Support

A number of techniques and applications have been developed for computers which are of potential use for a post-emergency decision support system. These are described in this section, and their potential application explored. In the following section, specific applications of these techniques within JSP2 are described.

Databases

Developments in database technology and computing power mean that very large amounts of disparate data can now be stored, accessed and manipulated rapidly. Moreover, this technology has now matured to the point where a degree of standardisation has been achieved, with many database systems using the Structured Query Language (SQL) to retrieve information. Sophisticated databases facilitate the connection of other software applications (for example geographical information systems - see below) and the development of flexible user interfaces, tailored for a specific purpose. An advanced database interface enables prompting for necessary information, screening for erroneous input and the simple construction of complex queries to the database. Information concerning the time of input, links between data and the history of manipulations carried out on the data can also be logged, facilitating quality assurance and retrospective analysis. Finally, triggers can be set, so that the user is alerted if particular data are entered, for example radionuclide concentrations exceeding given levels. Thus, the database can prompt the user to the most relevant information held at any given time.

Geographic Information Systems

At their most basic level geographic information systems (GIS) enable spatial information to be displayed and combined on a map. Even at this level, the GIS offers the decision maker a powerful tool for the communication and comprehension of complex information. The spatial distribution of data can be readily comprehended, and potential interactions between different spatial quantities can be identified. Combined with a relational database, simple map displays on a GIS can be used to present model results and time snapshots, and to assist in the exploration of data interactions (eg comparisons of measurements and model estimates). However, GIS are potentially far more powerful than simple map displays. The more advanced applications of GIS use spatial and temporal analysis techniques to maximise the amount of information that can be extracted from data. Whilst the use of GIS in this more complex manner is still very new in post-emergency management, applications such as automatic averaging of large volumes of data, or the 'intelligent' display of stored information on a scale appropriate to the scale of map being displayed, are examples of the future possibilities of GIS.

Multi-criteria Decision-aiding Techniques

Multi-criteria decision-aiding techniques offer the possibility of comparing protective strategies with competing and widely varying consequences. Implemented in computer systems, they provide a fast and flexible tool for evaluating strategy options according to criteria provided by the user. Implementations exist for ranking options, identifying the most influential attributes of the options, testing the sensitivity of the ranking to changes in the evaluation criteria, screening out options which could never be favoured, and developing hybrid strategies which combine the best features of those originally proposed. By linking such computer applications in a larger decision support system, the software could provide a user interface through which models were run to calculate strategy consequences, and all relevant parameters of the decision could be displayed in map form for ready assimilation.

Computer Networking

The speed and robustness of communication between computers is improving rapidly. The popularity of the Internet is a good example of how effective these links now are. Consequently, networking computers in different organisations and between different countries for post-emergency management is now a realistic goal. At a limited level, this should allow rapid data exchange between organisations with different expertise. However, the possibility of developing distributed databases (ie a single database that has component parts stored on different computers in different organisations) and accessing computer models held on other machines is now emerging. This has the advantage of removing the requirement for a single organisation to maintain an up-to-date compilation of all information and computer models relevant to an accident. Instead, each organisation can make its own data and particular models available to other organisations through the network, thus contributing one component of a larger, distributed decision support system.

Development of Decision Aiding Tools within JSP2

Within JSP2 research has been carried out with a view to: identifying more clearly the requirements of a post-emergency management support system; demonstrating the potential application of computer capabilities and techniques; and developing new models where gaps have been identified. The previous sections have described progress in the first area. In this section the specific computer applications and models developed within JSP2 are discussed.

Use of Measurements in the Post-Emergency Phase

One of the features of the post-emergency phase, compared with the emergency phase, is the existence of a much greater amount of measurement data. This, at the very least, enables predicted consequences to be compared with those observed, and, where measurements are particularly plentiful, for some endpoints to be estimated directly from these measurements. Within JSP2, two models have been developed which derive dose and related quantities empirically from measurement data.

The first(1) has been developed by the Ukrainian Scientific Centre for Radiation Medicine and uses whole body measurements of radiocaesium concentrations to determine the retrospective time profile of ingestion doses and to infer the intakes of radiocaesium in food which have led to these doses. By comparing the inferred actual intakes with the theoretical intakes based on consumption rate statistics and average radiocaesium concentrations in foods, much can be learned about local variations in concentrations and dietary habits and the effectiveness of food countermeasures.

The second(2) has been developed by the Gomel branch of the Institute for Radiation Medicine in Belarus. This model uses the observed relationship between ground contamination level, availability of privately produced milk (as measured by the ratio between the numbers of privately owned cows in a settlement and the number of people in the settlement), and the proximity of the settlement to a forest (ie a measure of the degree of access to forest foods) to average settlement ingestion dose. Using a combination of cluster analysis and linear regression techniques, empirical relationships (dose as a function of average ground contamination) for five types of settlements have been developed. Testing of this model has demonstrated a good correlation between estimated and actual dose (based on whole body measurements); a much better correlation than is obtained by applying a phenomenological model using regional parameters.

Development of a Risk Module and Database

The Kurchatov Institute, Moscow, together with BelCMT, Minsk have developed a risk module, BARD, for application within a post-emergency decision support system(3). This module is in some ways similar to the computer programmes ASQRAD and SPIDER developed by CEPN (France) and NRPB (UK), but contains a larger intrinsic database and includes non-radiological as well as radiological risks. This allows radiological risks to be compared with other health risks and should help in the allocation of resources devoted to protection. For a wide range of population groups (eg the population of a state, region city or settlement) and specific years, the database holds age distribution densities, which are further sub-divided according to gender and the fraction of population who are either rural or urban. For each type of health risk the database holds age-cause-specific death rates. The health risks considered include: infection and parasite diseases, malignant neoplasms, circulatory system diseases, respiratory system diseases, digestive system diseases, and accidents. For each of the general risk categories there is information on more specific injuries, for example the category malignant neoplasms contains information on leukaemia, respiratory cancer, breast cancer, digestive cancer, etc. For predicting future incidence and death rates, the risk assessment models of ICRP/UNSCEAR, BEIR V, RERF and NRPB are included in the module. Using these, lifetime risk, loss of life expectancy and incidence in specified cohorts and years can be calculated.

Agricultural Countermeasures Module

A regional to farm level module characterising the effects of changes and treatments to soil, crops and husbandry practice enables agricultural countermeasures to be assessed. This module provides information on the change in radionuclide concentration distributions in crops grown in regions of varying contamination level subject to a potentially complex set of user defined countermeasures. Information on the costs of actions are provided and, if required, the user is guided through the selection of countermeasure combinations. The models were developed and tested using data from the Kiev, Zhitomir and Bryansk regions.

Indirect Countermeasures Module

In the past, guidance on intervention after nuclear accidents has focused on countermeasures to reduce exposures to radionuclides released in the accident. However, experience after the Chernobyl accident has indicated that it is pertinent to consider another class of countermeasures - those aimed at improving the overall well-being of the population, without necessarily reducing the direct radiation exposure stemming from the accident(4). These have been termed indirect countermeasures and have been the subject of investigation within JSP2(5). Indirect countermeasures can be sub-divided into two categories: risk reducing indirect countermeasures and social action indirect countermeasures. The purpose of risk reducing indirect countermeasures is to reduce other risks the population is exposed to, for example those from radon, medical irradiation or chemical pollutants. Social action indirect countermeasures may be in the form of compensation, eg financial payments or improved amenities, or in the form of supporting actions to other countermeasures, in order to improve their effectiveness (eg information campaigns, local involvement in decisions).

In order to explore the application of indirect countermeasures after an accident, a computer module has been developed by the Institute of Biophysics. The module assesses the costs and benefits of applying countermeasures in three areas, two risk reduction applications, and one social action application. The risk reduction applications consider the costs and benefits of different radon treatment options and the costs and benefits of new equipment and training to reduce the dose received by patients having medical diagnostic examinations. This information can then be assessed by a decision maker who can decided how much weight to attach to these actions when comparing them against alternative direct countermeasures. The social action countermeasure is discussed in the next section.

Social Psychological Aspects

The Chernobyl accident has clearly demonstrated the importance of social and psychological factors after an accident. Research has been undertaken within JSP2 to quantify the influence of these factors, particularly with respect to their interaction with direct countermeasures. Although the complexity of this interaction means that only limited progress has so far been made, it is clear that some social and psychological factors can influence the dose effectiveness for direct countermeasures, whilst others can influence their monetary costs[6]. In future it should be possible to model these interactions explicitly by developing existing social-psychological models[eg 7], and to integrate the modelling within existing computer decision support systems. At present, a simpler approach has been adopted, that of providing the decision maker with additional information on social psychological factors relevant to particular countermeasures. For example, as part of the indirect countermeasures module, an informed assessment of the consequences of implementing a decision to relocate a population group in a variety of alternative ways is presented to the decision maker. The decision maker is then able to consider the dose, cost and health implications of particular relocation choices.

Display Methods

If information is to be assimilated efficiently by the decision maker, then it needs to be presented in a manner which facilitates this. RIARE, USCRM, and Topaz-Inform have all placed emphasis on developing appropriate display methods. For example, information can be presented in context using a GIS. The GIS display can show maps of the areas of interest at scales selected by the decision maker with additional information illustrating the current situation or the predicted consequences of a series of countermeasures. Standard graphic displays are also provided to show the variation in selected properties as a function of time. The decision maker or his representative interacts with the whole system through a series of menus which provide guidance for both an expert and novice user.

Linking between Different Computers

As a result of experimental investigations undertaken as part of JSP2, Topaz-Inform have developed a prototype model of a distributed problem-solving system. This model includes: the user interface (implemented on each computer under X-Windows), separate and different databases and models held on individual computers, and a calculation server to enable the user of one computer access to data and models on other machines. Data exchange between a group of modules takes place independently of other exchanges which are being transacted. The databases work in a multitasking regime and can therefore process several inquiries simultaneously. The system can link different types of computers and operating systems, for example, HP 9000 and PC486 computers and BSD Unix and SMOOTH operating systems.

Analysing the countermeasures at regional and local levels

Decision support should be available at all administrative levels from national to local. By bringing together many of the features and modules discussed above the PRANA (Protection and Rehabilitation of Agrosphere after Nuclear Accident) decision support system has been developed by RIARE[8] to achieve this.

PRANA is a GIS-based system which has been implemented for Novozybkov district in Bryansk region. The database includes detailed information on individual areas (field, settlement, ecology and radiological data including transfer factors) as well as the characteristics of the countermeasures (efficiency, costs etc). The system may be applied on any scale subject to the appropriate information being supplied.

The models used for estimating the contamination of agricultural products and the internal and external doses which result with and without countermeasures, are based on models developed within the framework of ECP9. A particular feature of the implementation of these models within PRANA is the development of procedures to undertake calculations using distributions of parameter values (as opposed to single value parameters).

The main functions of the system are in three areas:

- Database analysis: - this allows the selection of fields, settlements, farms etc. according to various criteria, for example, level of contamination, individual dose, collective dose.

- Assessment of countermeasures: - definition of a set of countermeasures for a specific area and for a specific duration. The analysis provides a set of radiological and economic indicators such as the cost-effectiveness.

- Indirect Countermeasures:- three sub-modules are included, as examples of the application of indirect countermeasures models within post-emergency computer decision support systems. Two enable the modelling of changes in radon exposure and doses from medical diagnostics, whilst the third provides information on some of the social-psychological implications of different implementation strategies for relocation.

By providing a user-friendly interface, and access to the data through Paradox 5.0, PRANA facilitates comparisons both of the consequences of alternative countermeasure strategies implemented at the local or regional levels and of how these consequences change with time.

The Way Forward

The experience of the Chernobyl accident, and the research carried out within JSP2 has improved the understanding of the needs of decision makers and how computer based decision support systems for post-emergency management can assist them. Key lessons are the need for any such system to be centred around a sophisticated relational database, holding a wide variety of data types in their spatial and temporal context. This in turn raises the need for continuously up-dated data: preliminary investigations within JSP2 at Topaz-Inform have indicated that a possible future system would consist of a distributed database, with a number of organisations each holding and being responsible for their own data. This is an area where further research could yield dividends.

Another key lesson is the need for post-emergency models to be developed that utilise collected data efficiently. In the immediate aftermath of an accident, it will usually be necessary to rely on simplified or averaging models. However, once more data become available, it is important that best use is made of these. In addition, there is a need to further develop methods for integrating model estimates, data and expert judgement, so that the best possible picture can be developed of both the accident impact and that of possible countermeasures.

A need has been identified for the inclusion of a number of models for each desired endpoint, so that the system can select and apply the most appropriate model, depending on the needs of the decision maker and the quality and quantity of data available. Finally, the need to develop interfaces that are more accessible to the decision maker has been identified. Both GIS and multi-criteria decision aiding packages have an important role to play in this. However, further research is required towards developing interfaces that enable the decision maker to ask more open-ended and 'natural questions', such as 'what strategies should I consider for this settlement/these settlements/this region/this farm?', 'what additional information could I collect in order to choose between these two strategies?'.

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