MOIRA-PLUS use in decision making on the long-term management of contaminated freshwater bodies and catchments.

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Abstract.

In the mid-long-term after a nuclear accident, the contamination of drinking water sources, fish and other aquatic foodstuffs, irrigation supplies and people's exposure during recreational activities may create considerable public concern, even though dose assessment may in certain situations indicate lesser importance than for other sources, as clearly experienced in the aftermath of past accidents. In such circumstances there are a number of available countermeasure options, ranging from specific chemical treatment of lakes to bans on fish ingestion or on the use of water for crop irrigation. The potential actions can be broadly grouped into four main categories, chemical, biological, physical and social. In some cases a combination of actions may be the optimal strategy and a decision support system (DSS) like MOIRA-PLUS can be of great help to optimise a decision. A further option is of course not to take any remedial actions, although this may also have significant socio-economic repercussions which should be adequately evaluated.

MOIRA-PLUS is designed to allow for a reliable assessment of the long-term evolution of the radiological situation and of feasible alternative rehabilitation strategies, including an objective evaluation of their social, economic and ecological impacts in a rational and comprehensive manner. MOIRA-PLUS also features a decision analysis methodology, making use of multi-attribute analysis, which can take into account the preferences and needs of different types of stakeholders.

The main functions and elements of the system are described summarily. Also the conclusions from end-user's experiences with the system are discussed, including exercises involving the organizations responsible for emergency management and the affected services, as well as different local and regional stakeholders. MOIRA-PLUS has proven to be a mature system, user friendly and relatively easy to set up. It can help to better decision-making by enabling a realistic evaluation of the complete impacts of possible recovery strategies. Also, the interaction with stakeholders has allowed identifying improvements of the system that have been recently implemented.

Keywords: Decision support systems; MOIRA DSS; freshwater ecosystems; long-term contamination; post-accident countermeasures

1. Introduction

In the mid-long-term period after a nuclear accident, the contamination of freshwater systems with radionuclides may affect drinking water sources, fish and other aquatic foodstuffs, irrigation supplies and people's exposure during recreational activities. Dose resulting from exposure pathways linked to radioactivity in water have in many situations lesser importance than other exposure sources, as clearly experienced in the aftermath of the Chernobyl or Fukushima accidents. However, they can create significant public concern and there is a need of reliable tools for a realistic evaluation of the water contamination problem and its evolution in time.

MOIRA ("MOdel-based computerised system for management support to Identify optimal remedial strategies for Restoring radionuclide contaminated Aquatic ecosystems and drainage areas") is a

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decision support system (DSS) for analysing mid-long-term management strategies applicable to freshwater systems contaminated with long-lived ^{137}Cs and ^{90}Sr. It was designed to allow for a reliable assessment of the long-term evolution of the radiological situation and of possible alternative management strategies, including an evaluation of their social, economic and ecological impacts in a rational and comprehensive manner. It was developed and tested during the 4th Euratom Framework Research Programme (EFRP) (Monte et al., 2000; Monte et al., 2002) and subject to additional testing and comparisons with other models inside the EVANET-HYDRA network of the 5th EFRP (Monte et al., 2005a). The latest version, MOIRA-PLUS©, incorporates many features derived from user's experience and feedback (Monte et al., 2009). It is a software tool to run quantitative evaluations of the fate of radionuclides deposited in the catchments or directly released to lakes and rivers. It assesses the dose to representative individuals and the collective dose and is able to simulate the consequences of selected interventions, calculating their costs and analysing benefits.

Evaluation of the end-users' practical experience with MOIRA has been performed both in the frame of the EVANET-HYDRA network (Monte et al., 2005a) and EURANOS project (Raskob, 2007) through demonstrations and practical exercises with the participation of both software developers and potential users and tests of application to specific scenarios.

The system has a number of users which provide feedback to the developers' team. This interaction has allowed identifying improvements of the system that have been recently implemented.

2. Main features and elements of MOIRA-PLUS DSS

DSS at all levels can be of great help when undertaking the analysis of the radiological situation in a given area or region, with a panoply of measures to improve the overall post-accident situation. Moreover, as ICRP recommends, "all the data, parameters, assumptions, and values that enter into the decision-making process should be presented and defined very clearly. This transparency assumes that all relevant information is provided to the involved parties, and that the traceability of the process is documented properly, aiming for an informed decision" (ICRP, 2006, para. 34). DSS like MOIRA can play an essential role in this process of informing the optimisation of post-accident management and providing traceability and transparency.

Post-nuclear accident DSS can range from a simple presentation of radiological data and related geographical / demographical information (level 0), to the analysis and prediction of current and future radiological situation (level 1), the simulation of potential countermeasures, determining their feasibility and quantifying their benefits and disadvantages (level 2) and, finally, the evaluation and ranking of alternative countermeasure strategies, by assessing the balance of their advantages (dose reduction, environmental improvement) and disadvantages (economic, ecological and social impacts, etc.) accounting for the judgements and preferences of the decision makers and stakeholders (level 3) (Ahlbrecht et al., 1997; Schulte et al, 2002).

MOIRA-PLUS has different components that integrate the main functions required at each level of decision. The main elements are the following:

- Validated models for predicting the time behaviour of contaminants (^{137}Cs and ^{90}Sr) in lakes, rivers and drainage areas (Håkanson and Monte, 2003) and well as the effect of selected countermeasures to reduce the contamination levels. These models have been tested and improved accounting for state-of-the-art techniques for modelling the processes of migration of radionuclides through the fresh water environment (Monte et al., 2003, 2004, 2005b). Some of the models have also been successfully applied to the marine coastal areas (Monte, 2011b). The functionality of MOIRA to analyse complex rivers systems and catchments is limited to the definition of not more than 20 river branches and reaches. These branches and reaches can be combined according to their shape features (tributaries of different levels and forks).

- Models to assess doses to man and biota (fish) and to evaluate the dose reduction obtained by implementing countermeasures affecting the direct human exposure to contaminated elements (Gallego and Jiménez, 2000). Their results should be combined with assessments of other exposure pathways, so that it may be possible to check if the target reference dose level for individuals is reached as recommended by the latest ICRP recommendations for long-term contaminated areas (ICRP, 2010).

- In lakes, a Lake Ecosystem Index (LEI) model to assess the impact of physical and chemical countermeasures on the lake ecological quality (Håkanson et al., 2000). LEI is a tool to give an account for the environmental (and not just radiological) consequences of chemical remedial measures (lake and wetland liming, potash treatment and lake fertilisation) carried out to reduce radionuclide levels in water, sediments and biota.
- A conceptually simple micro-economic approach to assess the economic cost of the different kind of countermeasures implemented in the MOIRA sub-models, which gives the user a full control on the basic data needed for the calculations (unitary costs).
- Methodologies based on multi-attribute analysis (MAA) techniques for ranking the different feasible interventions accounting for the above-mentioned impacts (Ríos-Insúa et al., 2006). In optimising intervention strategies one should include, obviously, health and safety and the tangible costs of protective actions, as well as other non-quantifiable factors such as reassurance, stress, and other societal values that should be taken into account by the decision-maker. Normally, these non-quantifiable factors can only be considered in a qualitative manner, and this is possible by using techniques like the MAA implemented in MOIRA.
- Software components implementing the above models and methodologies, combining all the components into one integrated DSS system and supporting the system with a user- friendly interface (Hofman, 2004).
- Data storage and analysis tools (Geographical Information System, GIS, and data bases) (Hofman, 2004).

2.1. Countermeasures

Available countermeasure in the event of radioactive contamination of aquatic ecosystems and their catchment range from specific chemical treatment of water bodies to bans on fish ingestion or on the use of water for crop irrigation. They can be broadly grouped into four main categories, according to their nature: chemical, biological, physical and social. Given the wide spectrum of actions available, a DSS like MOIRA can be indeed essential when trying to optimise a decision by accounting for single options or for suitable combinations of different remedial actions. Table 1 shows a list of countermeasures whose effects can be assessed by MOIRA-PLUS (Monte et al., 2009).

2.2. The MOIRA-PLUS software

MOIRA-PLUS is a user-friendly computer software system set in an environment based on PC and Windows®. To run MOIRA models it is necessary to install the software Powersim Constructor Run-Time. MOIRA also optionally requires the installation of MapInfo Professional for GIS data customisation and the visualisation of geographical maps in the GUI. Work to substitute MapInfo for freely distributed open source GIS software is currently in progress. The software framework was developed using Microsoft Visual C++. The GUI (see figure 1) has several tabs ("Site-specific data", "Case definition", "Strategies", "Results", "Optimal strategy", "Report") relevant to the steps of evaluating a scenario of environmental contamination enumerated below:

- Selection of the "target" object (lake, river, reservoirs) and definition of its site-specific characteristics (if site specific data are not available, default data can be supplied);
- Definition of the radionuclide contamination (time-dependent and, in the case of rivers, spatially distributed);
- Definition of alternative countermeasure strategies, i.e. flexible combinations of the available countermeasures;
- Running the sequence of models appropriate to the scenario;
- Running the MAA module in order to rank alternative management strategies;

- Producing a summary report containing information on source data, results and ranked management strategies.

Two versions of the DSS are available: a) MOIRA-PLUS-River that can be applied to complex networks of fresh water systems including lakes, rivers and reservoirs; and b) MOIRA-PLUS-Lakes that can be applied to single lakes and offers the possibility of assessing the effects of particular countermeasures such as water liming, potash treatment, catchment liming and application of fertilizers to lake water (Abrahamsson and Håkanson, 1997; Ottonson and Håkanson, 1997)

MOIRA-PLUS is free software that can be downloaded from the web-site https://sites.google.com/site/moirasoftware/home. From the same site it is possible to obtain documentation describing, in detail, the features of the decision support systems, the principles underpinning its functioning and some examples of applications and evaluations of its performance.

Table 1. Countermeasures that can be considered in MOIRA-PLUS for aquatic ecosystems and their mode of action (Monte et al., 2009).

Approach	**Action**	**Location of action**	**Mode of action**	**Experience, models & data**
Chemical	Potash treatment	Lakes, reservoirs, rivers	Chemical "dilution"	Some experience and data for lakes. Models available.
Chemical	Direct liming / catchment liming	Lakes, reservoirs, rivers	Changes pH, which influences for example biouptake	Considerable experience in relation to acidification. Models available.
Chemical	Fertilisation	Lakes, reservoirs, rivers	Increases biomass, "biological dilution"	Considerable experience in relation to eutrophication. Models available.
Physical	Control water flow through rate	Lakes, reservoirs, rivers	Change water retention time; open dams, fill reservoir, etc.	Site-specific. Limited experience, limited success. Models available.
Physico-chemical	Removal of contaminated sediments	Lakes, reservoirs, rivers	Reduction in active sediment layer and/or direct exposure to man	Little experience. Can be modelled.
Physico-chemical	Sediment traps	Lakes, reservoirs, rivers	Collection of radionuclides associated with particles	Tried after Chernobyl but unsuccessful. Can be modelled.
Physico-chemical	Removal of contaminated snow and ice	Lakes, reservoirs, catchments, rivers	Reduction in source term and/or direct exposure to man	Site-specific. No experience, but can be modelled.
Physico-chemical	Treatment of drinking water	Lakes, reservoirs, rivers	Reduction in dose from drinking water	Some experience after Chernobyl. Can be modelled.
Chemical/ Social	Food preparation	All ecosystems	Reduction in dose through food	Some experience. Can be very effective.
Social	Bans on fish consumption	Lakes, reservoirs, rivers	Reduction in dose through food	Some experience. Can be effective. Models available.
Social	Alternative drinking water sources, e.g. groundwater	Lakes, reservoirs, rivers	Reduction in dose from drinking water	Site-specific. Some experience. Effective. Can be modelled.
Social	Irrigation bans / Restrictions	Lakes, reservoirs, rivers	Reduction of uptake in crops	Some experience; can be effective. Can be modelled.
Social	Restricted areas	All ecosystems	Reduction in dose to population	Site-specific. Some experience; can be effective. Can be modelled.

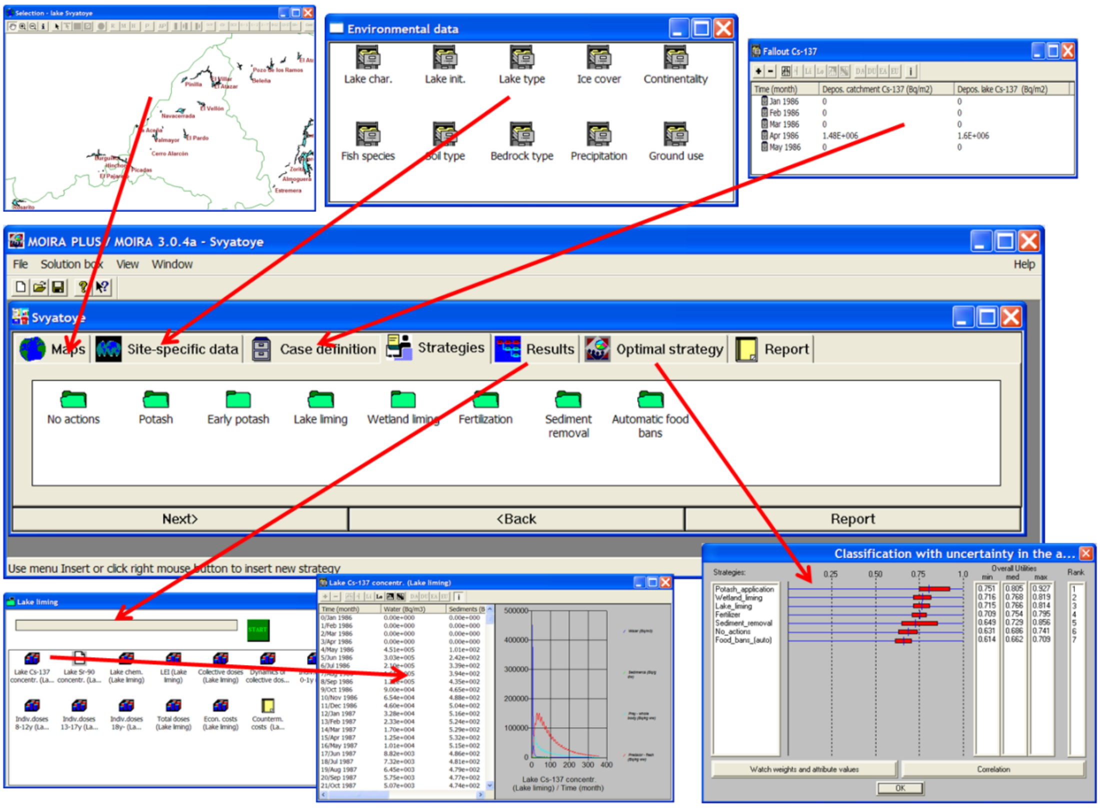

Figure 1. Overall view of MOIRA-PLUS graphical user interface (GUI) with a display of some of its main elements around: in the upper part, some of the elements necessary to define a case to be analysed; in the centre, the main window, with the alternative strategies being analysed; in the lower part, interactive display of results and ranking of strategies obtained from the MAA module.

3. End user's experience

Evaluations of the end-users' practical experience with MOIRA have been mainly performed in the frame of EVANET-HYDRA network (Monte et al., 2005a) and EURANOS project (Raskob, 2007).

In particular, within EURANOS, the demonstration covered two levels of activities: on the one hand, MOIRA was installed in an operational emergency management centre and was customised with the corresponding local and regional characteristics and data (Fig. 2). This was performed at the Nuclear Safety Council (CSN) of Spain. An application exercise in two phases was conducted there for an assumed accident scenario involving significant contamination of freshwater bodies in Spain (Gallego et al. 2009).

Also, MOIRA was distributed to several EURANOS partners, who installed the system, tested it and evaluated its functionality, ease of usage, and results obtained. The participants in demonstration tests evaluated the long-term evolution of ^{137}Cs contamination in fish and water in the lake Kohzanovskoe (Bryansk region, Russia) for the post-Chernobyl period and compared it against empirical data. They also tested different intervention strategies based on the countermeasures that the system is able to simulate, and analysed them with the MAA module.

More recently, MOIRA-DSS has been implemented and applied in the "Pays de Montbéliard" region in North-Eastern France. That region is crossed by the Doubs river, which is used as a unique source of potable water for the population and is also used for agriculture, livestock, fish farming, recreation including fishing and use of shores, etc. MOIRA has been used to study the vulnerability of the freshwater environment of the region and the consequences for the population in case of radioactive contamination. A scenario has been analysed simulating the potential radiological consequences that a nuclear accident in the Swiss nuclear power plant of Mühleberg could have on the Doubs river and its drainage basin (Biguenet et al., 2011).

Also, an application has been done to assess the impact of ^{137}Cs contamination of Chernobyl origin to 10 lakes and 18 rivers in Italy (Monte, 2011a). The aim was to show that MOIRA-PLUS can be easily customised to complex water systems by using data and information that can be obtained from different kinds of available sources. Site specific values of some aggregated transfer parameters were estimated for the most important Italian lakes. Although high values of fish and water consumptions were hypothesised, very low doses to public from the fresh water pathway following the accident were calculated.

All these applications have confirmed the flexibility of customisation of MOIRA by the users.

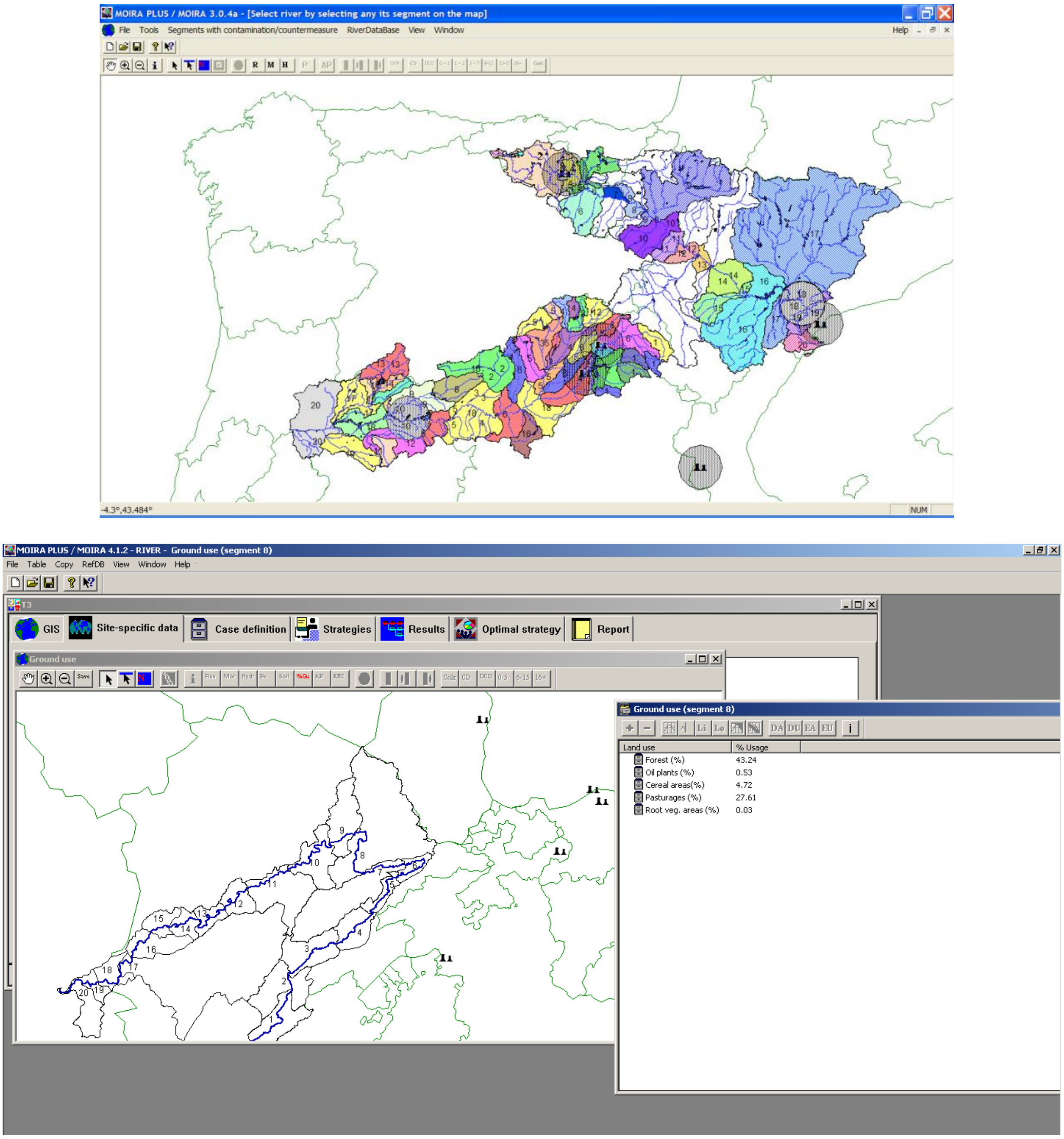

Figure 2. Two examples of MOIRA-PLUS customisation: the Tagus and Ebro rivers in Spain (up; Gallego et al; 2010) and the Doubs river in France (down; Biguenet et al., 2011).

3.1. Practical conclusions

The main conclusions from the exercise at CSN have been previously disseminated (Gallego et al., 2008; Gallego et al., 2009; Gallego et al., 2010) and the full technical reports of the activity can be found at the web-site https://sites.google.com/site/moirasoftware/documentation-and-publications (project EURANOS). For that exercise, a simulation of the contamination resulting from a severe accident leading to releases of ^{137}Cs and ^{90}Sr in the basin of the Tagus River was performed (contamination at the regional scale). In a very concise way, the main conclusions with regard to technical aspects were the following:

- Successful operational use may require that background environmental and socio-economic information are prepared in advance and maintained over time. Although definition of generic typical environments can be useful to get generic results, site specific peculiarities can be relevant to obtain representative results, which otherwise could be dismissed by local stakeholders and intervening agencies.
- The capacity to assess the economic cost of implementing countermeasures was considered as a very positive characteristic of MOIRA. However, base unit costs should be based on local specific information, if available.
- The system should have models to assess the dose to workers implementing countermeasures, at least those implying a higher contact with contaminated material, like sediments.
- The software was found easy to install, to use and to understand. Adaptation to regional settings did not seem to be overly complicated. The GIS support with MapInfo Professional is very good, with the advantage of the easy customization but the disadvantage of licence costs.
- Self-learning is possible, but users demand more complete documentation about the implemented models as well as some reference default exercises both for lakes and rivers that could help them to learn and run properly MOIRA system, including the most useful choices and advices in solving different tasks (for instance, concerning the application of some countermeasures).
- They also found the current software for decision analysis (MAA) not well enough integrated and slightly complicated.
- In summary, MOIRA was considered a good and useful tool, but with possibilities to improve.
- Also, it was emphasised that the users would like to use MOIRA and other computerised decision support system like RODOS-HDM (Zheleznyak et al., 2010) as complimentary DSS to perform short-term and long-term assessment and countermeasure evaluation for the aquatic environment. Establishing an automated data exchange between these DSS can simplify decision making and data input procedures for the users of both systems.

3.2. Conclusions on the use of MOIRA

Perhaps the most important conclusions were those related to organizational and preparedness aspects in response to radiological contamination events. From the experience and comments of the participants in the customisation/application exercises, it can be concluded that MOIRA is considered rather useful by the end users as software support for the management of contaminated fresh water bodies, with unique features for assessing consequences and countermeasures for a radioactive deposition on the surface of aquatic systems.

The exercise in Spain (Gallego et al. 2009) revealed the need for a better interface and understanding between agencies and stakeholders. It also demonstrated that the use of a user-friendly well-structured DSS is of aid to have a greater awareness of the respective competencies and capacities, helps cross-actor interactions and contributes towards a better common understanding of the important issues. This can facilitate in achieving a greater consensus among the different participants in the decision-making process in relation to the most appropriate actions for the management of the radiological consequences of a nuclear accident.

The scenario analysed in France (Biguenet el al., 2011) will also be used to discuss with different stakeholders (local professionals responsible of water management, local representatives, civil safety associations, firemen, police, etc.) the needs concerning radiation monitoring systems for water and food, drinking tap water or communication issues and to identify sensible points that should be included in the Geographical Information System of the territory which is used to identify and foresee natural and technological threats.

4. Final conclusions

MOIRA-PLUS has proven to be a mature system, user friendly and relatively easy to set up. It can help to reassure the public by enabling a realistic evaluation of the social, economic, and ecological impact of possible rehabilitation strategies after a fresh water contamination in case of a nuclear accident. Interaction with end-users has guided the recent improvements in the software system.

MOIRA-PLUS makes use of models that can be easily customised for the specific applications. Social and economic impacts are also incorporated into the framework. In summary, MOIRA provides a quick insight in the effectiveness of countermeasures, avoiding the choice of inappropriate or expensive strategies.

It can clearly aid cross-agency interaction and thus better common understanding of all related issues. It could also assist in the identification of water bodies where higher levels of contamination might be expected and in the definition of sampling and monitoring strategy.

Finally, by displaying a complete picture of the post-accident situation with regard to freshwater and management alternatives with their impacts, it helps to generate an aware consensus among the actors participating in the decision process concerning the management of the contaminated water bodies.

Similar conclusions could be applicable to other computerised DSS applicable to emergency preparedness and post-accident rehabilitation.

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