Journal of Environmental Radioactivity 225 (2020) 106444

Contents lists available at ScienceDirect

Journal of Environmental Radioactivity

journal homepage: http://www.elsevier.com/locate/jenvrad

Review

Role of modelling in monitoring soil and food during different stages of a nuclear emergency

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ARTICLE INFO

Keywords:
Nuclear emergency
Decision support systems
Terrestrial food chain
Environmental monitoring
Radioecological models

ABSTRACT

In case of a nuclear accident, adequate protection of the public and the environment requires timely assessment of the short- and long-term radiological exposure. Measurements of the radiation dose and the radioactive contamination in the environment are essential for the optimization of radiation protection and the decision making process. In the early phase, however, such measurements are rarely available or sufficient.To compensate for the lack of monitoring data during nuclear emergencies, especially in the early phase of the emergency, mathematical models are frequently used to assess the temporal and spatial distribution of radioactive contamination. During the transition and recovery phase, models are typically used to optimise remediation strategies by assessing the cost-effectiveness of different countermeasures. A prerequisite of course is that these models are fit for purpose. Different models may be needed during different phases of the accident. In this paper, we discuss the role of radioecological models during a nuclear emergency, and give an outlook on the scientific challenges which need to be addressed to further improve our predictions of human and wildlife exposure.

1. Introduction

In the aftermath of the Chernobyl accident, a range of decision support systems (DSS) have been developed to provide decision makers with a wide range of data during the different phases of a nuclear emergency. Whereas some of these DSS apply across the different emergency phases and to different ecosystems, others are specific to certain phases and ecosystems.

In Europe, the Real-time Online Decision Support System for nuclear emergency management (RODOS) is widely used as a comprehensive decision support tool (Raskob and Ehrhardt, 2000; Vamanu et al., 2004; Dvorzhak et al., 2012; Landman et al., 2014; Leung et al., 2018). It consists of specialised models that simulate the radionuclide dispersion in the atmosphere, aquatic and terrestrial ecosystems and the food chain. It also has integrated models to calculate doses to humans resulting from different exposure pathways.

Examples of other DSS used worldwide are RECASS (Shershakov et al., 1993), ARGOS (Hoe et al., 2009), NARAC (Modelling and Decision Support System for Radiological and Nuclear Emergency Preparedness and Response) (Bradley, 2007) and (W)SPEEDI (Chino et al., 1993). Examples of specific DSS are MOIRA (Monte et al., 2000), STRATEGY (Cox et al., 2005; Hoe et al., 2009), both funded by the EC and the RESCA tool resulting from IAEA Technical Co-operation projects (Ulanosky et al., 2011). The specific models are decision support tools for optimising management strategies for contaminated areas; MOIRA for lakes and rivers and STRATEGY and RESCA for agriculture. These DSS tools have a multi-attribute analysis module to rank the countermeasures based on radiological, social and economic criteria (Shershakov et al., 2009). The MOIRA model has been implemented in RODOS and ARGOS platforms.

Here, we review the application of DSS and their radioecological models (generally containing a food chain and dose assessment component) to aid management of nuclear emergencies with reference to the radioactive contamination of terrestrial food production systems. Specifically, how models have been used to derive guidance levels, support monitoring, plan remediation and map radioecologically sensitive regions. We draw on experience and lessons learned from the application of such models to manage the consequences of the Chernobyl and Fukushima accidents. The paper also summarises the main developments in the nuclear emergency management since the Fukushima accident. The scope of this paper is limited to the food production systems (mainly pasture and croplands). We end the review with

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https://doi.org/10.1016/j.jenvrad.2020.106444
Received 19 December 2019; Received in revised form 15 July 2020; Accepted 4 October 2020
Available online 23 October 2020
0265-931X/

an outlook on the scientific challenges to be addressed in order to improve radiological impact assessments. In the supplementary material, we present illustrative examples of model application during nuclear emergencies based on two hypothetical emergency response scenarios and one real transition phase scenario. The scenarios relate to soil and food contamination arising from atmospheric deposition of radioactive releases during a nuclear accident. These examples show how the model results can complement the monitoring results and vice versa.

2. Role of radioecological models during nuclear emergency

To ensure adequate and timely response, international guidance recommends distinction between the emergency response, which is further divided into urgent and early response phases, and transition phases during a nuclear or a radiological emergency (IAEA, 2018). The distinction is based on the timescales in which specific protective actions (e.g. prevention of ingestion of potentially contaminated food, milk or drinking water) are needed to achieve the goals of the emergency response. The following sections review the role of radioecological models in the effort to prepare for and respond to nuclear emergencies.

2.1. The emergency response phase

In this phase of an emergency (lasts from days to weeks), local agricultural produce might become contaminated due to radioactive deposition (mainly contamination of milk with radioiodine and food crops if release occurs during the growing season). Therefore, restriction of the distribution and consumption of certain food- and feedstuffs might be necessary to protect the public from unacceptable radiation exposure. Food restriction depends on the level of contamination in the food- and feedstuffs and requires quantitative assessment of the severity of the contamination. Radioecological models may be used, during the preparedness stage, to derive operational levels to guide decision-makers concerning the necessary protective actions required (e.g. exclusion of pasture, indoor feeding of cattle, rejection of milk) (Balonov et al., 2018; Codex Alimentarius CXS 193-199, 1995; EC, 2016). Operational Intervention Levels (OILs) and the Permissible Levels are examples of operational guidance levels derived from radioecological models.

2.1.1. Establishing Operational Intervention Levels (OILs)

Operational Intervention Levels (OILs) are guidelines that help timely implementation of predetermined countermeasures in case of a nuclear emergency (IAEA, 2017). For instance, consumption and distribution of local produce should be restricted in areas where measured ambient dose rate exceeds 1 μSv/h (OIL3). Restrictions based on OIL3 should be revised once contamination has been measured in food, milk and drinking water; if it exceeds 200 Bq/kg ^{137}Cs or 1000 Bq/kg ^{131}I (OIL7), then restriction should be continued.

Radioecological models were used to derive the OILs based on the ingestion dose to members of the public expected to receive the highest dose from consumption of contaminated food. The OILs reflect radionuclide mixes representative of a wide range of postulated or observed fuel damage scenarios and releases. Radionuclide interception by plant foliage, radioactive decay, weathering were also considered, while food processing is not considered. (IAEA, 2017).

Although the OILs are instrumental to the prompt response to a nuclear emergency, their use should be restricted to the early phase when monitoring data of the food chain are sparse or not yet available. Once available, measurements of radioactivity concentration in food- and feedstuffs should be used and directly compared with the maximum permissible limits to decide on longer term agricultural countermeasures.

2.1.2. Establishing permissible and guidance levels

To limit public exposure to radiation through ingestion of contaminated foodstuffs, permissible levels (PLs) have established that set a limit on the radioactivity in various foodstuffs in the event of a nuclear emergency. A PL is set such that the overall internal exposure (expressed as annual dose) from ingestion of foodstuffs at this level is below a certain limit. For instance, Temporary PLs (TPLs) were introduced in the USSR following Chernobyl accident with reference to the activity concentration of ^{131}I, ^{134,137}Cs and ^{90}Sr in milk, dairy products and meats. In the European Union, Maximum PLs (MPLs) were establish to control food imports and protect consumers in the wake of the Chernobyl accident (EC, 1987) and recently the Fukushima accident (EC, 2016). The Codex Alimentarius Commission (a body established jointly by the Food and Agriculture Organization and the World Health Organization) recommends guidance levels (GLs) for maximum activity concentrations in food moving in international trade (Codex Alimentarius CXS 193-199, 1995). Table 1 compares PLs in use in different regions.

Permissible and guideline levels are typically derived using dose assessment models and information about the radionuclides (ingestion dose coefficients), dietary habits of the 'reference' individual (annual consumption rate and how much of their diet is contaminated) and the contamination level in their food. For instance, starting from an annual radiation dose of 1 mSv, the EU MPLs are back-calculated based on a generic human diet of which 10% is contaminated. When considering international trade, foodstuffs whose contamination is below the guideline are considered safe for human consumption and international trading, whereas those whose contamination exceeds the guideline levels, national governments shall decide whether and under what circumstances the food should be distributed within their territory or jurisdiction.

In Belgium, OILs have been derived from the EU MPLs using a food chain model (Govaerts et al., 1983) to calculate peak concentrations in different food products as result of radioactive deposition on plant and soil-plant uptake (Table 2). The model accounts for losses due to radioactive decay, weathering and leaching from the root zone. The Belgian OILs, given in levels of radioactivity deposited on the soil, can easily be compared with monitoring data and, in case these are not available or insufficient, with site-specific predictions of deposition obtained using atmospheric dispersion models, also in Bq/m^2 for the food chain. Once monitoring data for food are available, values in Table 1 can be used.

Because the PLs are typically derived from model calculations, they greatly depend on the underlying assumptions of those models. These differences include the consumption rate, the fraction of contaminated food in the diet (10% EU and 30% USA), the intervention level for ingestion (5 mSv/y in the USA and 1 mSv/y in EU) and the ingestion dose coefficient. Consequently, PLs may vary between countries as Table 1 shows.

2.1.3. Supplementing monitoring

The radioactive release and meteorological conditions could be very dynamic in the early days of the emergency, which results in complex spatial and temporal deposition patterns. Resources are often too limited to cover all potentially affected areas, which delays collecting and analysing environmental samples. Consequently, monitoring data may be insufficient or uncertain. During the Chernobyl accident for instance, immediate setup of monitoring programmes was only possible in a few areas around the nuclear power plant (Fesenko et al., 2007). In Fukushima and following the tsunami, early environmental monitoring was hampered by insufficient infrastructure and limited resources (e.g. dangerous road conditions, shortages of fuel, damaged monitoring equipment) (IAEA, 2015). Consequently, sampling of food and water for monitoring surveys started few days after the initial release; first food monitoring data were available for a limited number of food samples on March 16, 2011 (Hamada et al., 2012). 'Contaminated beef began to be detected after it had been distributed and consumed for several months' according to Hamada et al. (2012) who attributed the undetected

Table 1
Maximum permissible levels in food for free trade.

Radionuclide	Food (Bq/kg)								
	Infant food			Dairy/Dairy produce			Other food		
	EU	USA	CODEX	EU	USA	CODEX[a]	EU	USA	CODEX
^{231}Pu,^{241}Am	1	2	1	20	2	–	80	2	10
^{90}Sr	75	160	100	125	60	–	750	160	100
^{131}I	150	170	100	500	170	–	2000	170	100
^{134}Cs,^{137}Cs[b]	400	1200	1000	1000	1200	–	1250	1200	1000

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[a] There is no dairy food category in Codex.
[b] In the EU legislation, this category includes not only ^{134}Cs, ^{137}Cs, but all radionuclides with a half-life > 10 days, except ^{3}H, ^{14}C and ^{40}K.

Table 2
Belgian derived intervention levels for the protection of the food chain in nuclear emergency situations (Bq/m^2).

Radionuclide	Vegetables	Milk	Meat
^{241}Am	400	8,00E+06	8000
^{134}Cs	6000	10000	10000
^{137}Cs	6000	10000	10000
^{131}I	10000	4000	40000
^{90}Sr	4000	10000	3,00E+05
^{239}Pu	400	8,00E+08	8,00E+07

contaminated beef to either the limited number of food samples analysed or the miscommunication between local authorities and farmers (feeding the cattle with contaminated rice straw caused the elevated Cs concentration in beef).

Radioecological models can preliminarily assess food contamination, pending further confirmation by monitoring data (Whicker and Kirchner, 1987; Brown and Simmonds, 1995; Müller and Pröhl, 1993). These models estimate human exposure from ingestion of contaminated food based on actual or projected ground deposition (Katata et al., 2012; Terada et al., 2012), characteristics of agricultural systems (soil and crop type, agricultural practices, etc.) and public dietary intake. Model predictions can also be used to guide and prioritise field monitoring and make best use of available resources.

Radioecological models can require different types of site-specific data that are not always available. In such cases, the model can be set up using generic (default) parameters and provide results that serve as a reference. In case of a real nuclear incident, the model predictions must be verified using data from existing monitoring networks or from post-accident field monitoring campaigns. Given the high uncertainty associated with the source term and other model parameters during the acute phase, monitoring data should, when they become available, be used to reduce the uncertainty in model predictions.

2.2. *The transition phase*

An effective remediation strategy depends on many, often intricate, factors such as contamination severity and heterogeneity, prevalent environmental conditions, implementation cost and socio-economic implications (Shershakov et al., 2009).

Models assist decision makers to optimise remediation strategies by allowing them to 'virtually experiment' with different remedial options; in other words, the impact of a given remediation strategy can be evaluated without having to implement it. This cost-free experimentation is advantageous given the high cost and repercussions associated with certain strategies (e.g. changing agricultural practices or land use) (Fesenko et al., 2013). Coupled to spatially distributed agricultural and human diet data, radioecological models have extensively been used in Europe following the Chernobyl accident to predict long-term contamination of agricultural produce, identify areas with enhanced radionuclide transfer to food chains and propose remediation strategies (van der Perk et al., 2000, 2001; Cox et al., 2005; Gillett et al., 2001; Jacob et al., 2009; Gering et al., 2010; Fesenko et al., 2013).

Decisions concerning the need of remediation and selection of the remediation strategy are quite complex because several factors such as the radiological relevance, technical feasibility, socio-economic factors (e.g. economical cost, cultural heritage, ecosystem services) have to be considered. Additional decision-aiding techniques such as cost-benefit analysis or multi-attribute utility analysis are often used to facilitate the ranking and selection of the remediation strategies. (Shershakov et al., 2009).

3. Mapping radioecological sensitivity

Experience shows that the radioactive surface contamination level conveys little information regarding the capacity of agricultural lands to transfer radionuclides to food chain. Soil properties, plant species and management practices all contribute to radionuclide transfer to food chain and human exposure. Consequently, the highest human exposure does not necessarily coincide with the most contaminated areas as many post-Chernobyl studies have demonstrated. For instance, according to some estimates (Prister et al., 2018), human exposure near the 30 km Chernobyl exclusion zone was 10 times lower, despite the higher deposition, than that in the Polissye region, several 100 km from the ChNPP. Because ^{137}Cs transfer through soil-pasture-milk pathway was underestimated, agricultural countermeasures were delayed, by two years, and contamination in milk exceeded the national standard in Polissye (Maloshtan et al., 2017).

The concept of radioecological sensitivity (Aarkrog, 1979; Howard, 2000; Howard et al., 2002) is more helpful than deposition density in identifying areas vulnerable to radioactive deposition. It considers not only the deposition density, but also the relevant exposure pathways, environmental factors (radionuclide accumulation and bioavailability in environmental media), agricultural production and human habits. Because many of these factors vary spatially and temporally, radioecological sensitivity is space- and time-dependent. Dynamic environmental transfer models with spatially distributed inputs (van der Perk et al., 2000; Absalom et al., 1999, 2001) are then essential to assess radioecological sensitivity.

Mapping radioecologically sensitive regions enables decision makers to prioritise and evaluate monitoring and remedial strategies based on realistic criteria. This mapping has been achieved by coupling dynamic transfer models to a geographical information system (GIS) often to form an Environmental Decision Support System (EDSS). The GIS provides the transfer models with spatial inputs such as land use, soil characteristics, agricultural production and consumption rates (IAEA, 2013; Tracy et al., 2013; Prister et al., 2018). An EDSS outputs activity concentrations in foodstuffs, radionuclide flux from an area via a given food product and maps of regional radioecological criticality index, which is the landscape ability to accumulate in plants and accidental transfer of radionuclides to humans.

4. Main developments since the Fukushima accident

Several DSS for managing a nuclear emergency have been developed and improved over the last three decades. Although these tools have reached a certain level of maturity, there are aspects that require further improvement. A summary of the recent developments and on-going research topics are given below.

Fast and reliable forecasts are one of the key factors of a well-functioning nuclear emergency system. Automatic integration of monitoring data into existing DSS would reduce the time needed to improve the reliability of their outputs. Interest in techniques for combining monitoring data and models (i.e. data assimilation) has increased over the past two decades. The European Data Assimilation for Off-site Nuclear Emergency Management project (DAONEM, 2000–2004) specifically addressed a practical improvement in the real time on-line decision support system (RODOS) by developing and integrating a data assimilation capability for off-site nuclear emergency management. Improvements of the monitoring strategies and their implementation in the modelling tools have been further explored in European projects HARMONE (EC, 2017; Gueibe et al., 2017) and CONFIDENCE (Bleher et al., 2019). Data from citizen monitoring can supplement the operational monitoring data and should also be included in the modelling and decision making. Full automatic integration of the monitoring data into DSS tools is still lacking. The management of the uncertainties and quality of the measurements and ways of integration into the modelling tools needs further investigation (Raskob et al., 2020).

Several sources of uncertainty affect the output of the DSS tools (Walker et al., 2003; Salbu, 2016; Urso et al., 2019). Generally, there are uncertainties related to the interpretation of the scenario, the model parameters and the model representation of the real system. Some uncertainties are due to lack of knowledge of processes and the way in which these interact and can be reduced by improved understanding while others are due to inherent variability. Often, simplifying, conservative assumptions are used to address the uncertainties especially those related to the scenario and/or parameters, which may lead to overestimations of the dose impact and, as result, unnecessary protective actions. These uncertainties are particularly high in the early phase of the accident. While the uncertainty of several model parameters can be reduced by collecting site-specific data during the preparedness phase, accident (scenario) specific data (e.g. source term, meteorological conditions affecting the surface contamination) are not known at the beginning of the accident (Hernández-Ceballos et al., 2020). As more measured data become available, the model calculations can be refined and uncertainties be reduced. Nevertheless, given the inherent variability of environmental data and gaps of knowledge concerning the environmental behaviour of radionuclides, uncertainties are an intrinsic part of the modelling results during all phases of the accident. Therefore, it is useful to consider quantitative and qualitative approaches to estimate the uncertainties of the contamination of the food chain as it will indicate the level of confidence in the estimates. Approaches to enhance the flexibility and defensibility of uncertainty handling, and provide the necessary structure for integrating probabilistic models into a DSS have been developed, but need further improvement before implementation (Leonelli and Smith, 2013; French et al., 2017). However, probabilistic models cannot accommodate for all uncertainties. The possible impact of qualitative uncertainties is generally based on expert judgment without formal rules. To increase the traceability of the decision making and reduce the risk for poor or ineffective implementation of countermeasures, formal approaches on how to deal with qualitative uncertainties also need to be incorporated in the decision making (French et al., 2017). Handling and reducing uncertainties in the decision making for nuclear emergencies has been the topic in the European research projects CONFIDENCE (Raskob et al., 2018, 2020) and TERRITORIES (Urso et al., 2019). Several approaches to handle the uncertainty has been proposed in the CONFIDENCE project (Raskob et al., 2020) such as the ensemble modelling (i.e. running the same model with different set of realistic environmental conditions) for atmospheric source term modelling (Korsakissok et al., 2019).

There are also uncertainties related to the interpretation of model results by the stakeholders and the public. Social aspects, such as the behaviour of the public during a nuclear emergency and involvement of the stakeholders in the decision making process, are being studied (Perko et al., 2019). Multi-criteria decision analysis and cost-benefit analysis are methods that have been used to compare remediation alternatives by considering the environmental, technical, economic and social aspects for contaminated areas. However, although the social aspects are important, it is difficult to quantify the social criteria. Discussions with the stakeholders from the beginning of the decision process as well as better ways of communication may help to address social concerns such as public acceptability, confidence in the assessment results, concerns of health and safety problems during the remediation works and reduce the uncertainties related to these concerns (Raskob et al., 2020).

In order to increase confidence in their predictions, radioecological models should incorporate relevant environmental processes at the right level of mathematical simplification. Process-based (also referred to as mechanistic) radioecological models are developed based on the understanding of radionuclides' behaviour in the environment. Conversely, empirical radioecological models are largely based on empirical data that are specific to certain sites. Although process-based radioecological models may outperform their empirical counterparts when predicting the fate of radioactive substances in the environment (Hinton et al., 2013), they may require more data, so the conceptual uncertainty of these models can be reduced at the expense of increased parameter uncertainty. Consequently, process-based models are often less practical in nuclear emergency contexts where data availability is limited (e.g. in the early days). Semi-mechanistic models may be more appropriate as these models strike a good balance between process-based and empirical models. A semi-mechanistic model accounts for the relevant environmental processes and characteristics with reasonable data requirements, and it is fit for predicting radionuclide transfer (e.g. to the food chain) during nuclear emergencies (Almahayni et al., 2019a).

A few DSS (e.g. EDSS (van der Perk et al., 2000)) already use a semi-mechanistic soil-plant transfer model (Absalom et al., 2001). The Absalom model, whereby the soil-plant transfer factor of ^{137}Cs is estimated, based on a few soil properties (i.e. clay content, exchangeable K, pH and organic matter), has been used in several studies with varying success. Such an approach can present better the dynamics of the radiocesium cycling in terrestrial environment than a constant soil-plant transfer factor (Almahayni et al., 2019b), but is not applicable on the carbonate soils of the Marshall Island atolls and their vegetation (Simon et al., 2002). It also tends to underestimate the Cs uptake by crops grown on Japanese soils (Uematsu et al., 2015, 2016 and performs better for grass than for other crops (Rahman et al., 2005; Almahayni et al., 2019b). The findings suggest that the Absalom model which was developed for temperate European soils, needs further calibration and validation using other soils and plant types than the ones considered in its development. The use of semi-mechanistic models for other radionuclides (e.g. Sr) released during a nuclear emergency has also been studied recently (Almahayni et al., 2019a; Beresford et al., 2020).

The performance of semi-mechanistic soil-plant models for both Cs and Sr have been compared with the steady state soil-plant transfer factor model of the FDMT (Food Chain and Dose Module for Terrestrial Pathways) model that is implemented in the DSS tools ARGOS and RODOS. It was concluded that, compared with the soil-plant transfer factors, the use of semi-mechanistic models gives a better identification of the most vulnerable agricultural areas after a nuclear accident in terms of enhanced food chain transfer (Brown et al., 2020).

Another pathway by which radionuclides can enter the food chain is foliar uptake. For atmospheric releases, foliar uptake is the main pathway on short term if plants are present on the land during the passage of the plume, while on longer term the root uptake becomes more important and will dominate in the recovery phase. Foliar uptake of radiocaesium was also the main source of the contamination of forest following the Chernobyl accident (up to 90%) (IAEA, 2002). There are studies on foliar uptake by food crops (Tschiersch et al., 2009; Henner et al., 2013; Hurtevent et al., 2013) but, compared to the root uptake, the foliar uptake is much less studied and studies mainly focus on herbaceous vegetation (IAEA, 2010; Gonze and Sy, 2016). Several factors, such as plant species, meteorological conditions, physico-chemical form of the radionuclide (ionic charge, aerosol/gas, particle size), and type of deposition (dry/wet) may influence the interception and uptake by plants (Thiessen et al., 1999; Tschiersch et al., 2009; Bengtsson et al., 2012). How these factors influence the foliar uptake (interception, retention and translocation) is still poorly understood. Most studies do not analyse all factors that could have an impact or report them in different ways, making it difficult to compare results. Models to estimate the dry interception (Chadwick and Chamberlain, 1970; Vandecasteele et al., 2001) and wet interception (Müller and Pröhl, 1993; Pröhl, 2009) have been developed, but their results are highly uncertain and mainly indicative as, for most crops, no data for parametrisation are available. The retention on the leaves and translocation within the plant to edible parts are even less studied than the interception. Retention is often presented by a weathering rate and translocation by a single constant value (IAEA, 2010). More experimental studies are needed considering systematically the different processes and factors controlling the foliar uptake (Pröhl, 2009; IAEA, 2010).

The Fukushima accident has emphasised the need for environmental data and data on human habits and agricultural practices for regions other than the European temperate climate. Projects have been set up to gather information for other climates such as the boreal, (sub)tropical and (sub)arctic environment (Staudt, 2016a, 2016b; Thørring et al., 2016; El Shazly et al., 2019; IAEA CRP D15019, 2019-2024); IAEA MODARIA, 2019; Guillén et al., 2019) and expand the databases of the DSS tools to make them broadly applicable.

The Fukushima accident resulted in the release of large quantities of radioactive material to the ocean threatening the aquatic wildlife and food chain (Tsumune et al., 2020). The contamination of the marine environment near Fukushima was the result of direct discharge into the aquatic environment and atmospheric deposition. Most DSS did not perform well because the models and data were based on the experiences from the Chernobyl accident (Bailly du Bois et al., 2014; Duffa et al., 2016; Vives et al., 2018), and because the process was highly dynamic. The DSS could not handle the source term for the marine environment which was quite different compared to the source term of the Chernobyl accident, i.e. atmospheric deposition and a highly time-variable aquatic release in coastal and marine environments in case of Fukushima versus short-term atmospheric release in case of Chernobyl. As result, more research has been done on the dispersion models for aquatic environment (rivers, coastal, marine) (Bailly du Bois et al., 2014; Periáñez et al., 2015; Duffa et al., 2016; Kobayashi et al., 2017; Tsumune et al., 2020) and biokinetic models and databases for the transfer to marine wildlife have been developed (Beresford et al., 2015; Vives et al., 2018). In particular, in the case of Fukushima, it was found by the latter authors that a biokinetic model based on kinetic uptake and release with a multicomponent biological half-life is required to give the best results both in the short and the long term.

5. Research needs

Research priorities in the field of radioecology and nuclear emergencies are described in the European Strategic agenda (Hinton et al., 2013; Strategic Research Agenda of the NERIS platform, 2019), produced with the help of the ALLIANCE[1] and NERIS platform[2].

The key challenge for both platforms is to improve scientific knowledge on human and wildlife exposure to ionising radiation, which can lead to better assessment methodology in all phases of a nuclear or radiological event. This can be reached by developing a more scientific based knowledge of the environmental processes, building this information into assessment tools to calculate the distribution and transfer of radionuclides in the environment. By filling knowledge gaps along with having better monitoring tools and better quality of data to parametrise the tools, a more fit for purpose and accurate assessment methodology can emerge. We will discuss priority research topics of this challenge in further detail in the next sections.

5.1. *Priorities on modelling tools*

The development of models at landscape level and linking these to local models, followed by the incorporation of a suit of appropriate models into the DSS is one of the research topics. Practical radioecological models that consider the process interconnections at various biosphere interfaces in aquatic and terrestrial ecosystems and that make predictions at landscape level are not yet well developed, making it difficult to address the cycling and distribution of radionuclides in dynamic landscapes. The current spatially-resolving models only address local processes (Cox et al., 2005, van der Perk et al., 2000). The key problem is that the experimental studies are generally short-term and small-scaled and extrapolation of the data and conclusions to larger scales is difficult, due to lack of systematic knowledge. What is needed is more process-based research to understand the processes that may be important in the cycling and long term fate of radionuclides at landscape level (e.g. erosion, resuspension, etc.). A first step in this direction are the models that link thematic maps of key factors such as topography, land use, soil type and other soil characteristics to the radionuclide deposition maps (van der Perk et al., 2000). By mapping the measured temporal and spatial transfer data linked to the thematic maps, such models help to address important knowledge gaps on the cycling and redistribution of radionuclides in the environment.

As the ingestion dose is often the main exposure pathway on the long term ($>$ 1 year after a nuclear emergency without countermeasures), reducing the uncertainties of the soil-to-plant predictions remains a priority. The development of process-based models which are globally applicable (i.e. transferable), along with the gathering of appropriate datasets for various environmental conditions, should result in more realistic and accurate models for radiological impact assessments. Other important topics are (a) the identification and characterisation of the sources of uncertainty and (b) guidance on how to deal with variability and uncertainties in models, a line of research already initiated under the EC CONCERT projects CONFIDENCE and TERRITORIES.

Regarding exposure to non-human biota, especially for the transfer of radionuclides to marine organisms, it is necessary to introduce food web modelling in order to estimate the migration of radionuclides at various trophic levels. The areas that need more research are the interaction between the seawater, the suspended particles and bed sediment as well as the transfer through the aquatic food chain, because there are large sources of uncertainties and a shortage of experimental research to generate model parameters in these departments (Vives I Batlle et al., 2018). The same authors highlight the importance of gaining further knowledge on the role of sediments as a sink for radionuclides, leading to their long-term impact to the benthic food chain.

5.2. *Priorities on data collection and analysis*

With 450 operational nuclear power plants (NPP) and 53 NPP under

[1] http://www.er-alliance.org.

[2] https://www.eu-neris.net/

construction (IAEA, 2020), the nuclear power sector is expanding in many environments, leading to a need for more data on the fate of radionuclides in under-explored regions such as, boreal and (semi)-arid regions. In addition, floating reactors have become operational, allowing to operate at very different environments in large parts of the world (Standring et al., 2009). The current DSS toolset needs to be expanded (e.g. with parameters for local food products, new remediation options) in order to be also applicable to these regions. Moreover, data updates are regularly required as the composition of the human diets change. Experimental work in both laboratory and field domains is necessary to calibrate and validate the models. However, as it will be impossible to gather appropriate data for all crops and animals in all environments, novel extrapolation approaches based on phylogenetics (Willey and Fawcett, 2006; Beresford and Willey, 2019), ionomics, allometrics or ecological stoichiometry (Beresford et al., 2016) offer a solution to estimate the transfer parameters and thus concentrations in food products and biota for which there are data gaps.

In large-scale nuclear emergencies, the amount of geo-statistical datasets is overwhelming, leading to increases in response time. Advanced computational techniques are required to analyse these large datasets so as to predict the fate of radionuclides at landscape level. Interpolation tools like geo-statistical techniques can combine and analyse different spatio-temporal datasets, producing predictions for the unsampled locations (Desnoyers and Dubot, 2012). Artificial Intelligence and more specifically Machine Learning (ML) is another promising computational technique. Since ML-techniques do not require statistical preconditions regarding the nature of the concerned data, like independency or uncorrelatedness, to be fulfilled, it is especially interesting in the context of unexpected events or episodes such as nuclear emergencies (Gokaraju et al., 2017; Woo, 2018). Although ML has become the preferred approach for interpreting big spatio-temporal datasets in terms of functional information and recommended decisions (Aquilina et al., 2018; Ottoy et al., 2018; Samardžić-Petrović et al., 2017; Wang et al., 2016), it remains relatively underexplored as a technique for modelling the radionuclide transfer and exposure.

5.3. Priorities on measurement methods

The development of new modelling tools leads to the need for new, appropriate data for the parametrisation of these modelling tools as well as the need for new rapid analytical methods to handle the increasing amount of samples. For example, Mid Infrared Spectroscopy is a promising fast measurement tool commonly used for the derivation of soil physico-chemical characteristics such as soil water capacity, organic matter as well as being an analytical aid for the derivation of solid-solution partitioning coefficients for cationic metals, such as in soils at European scale in the GEMAS project (McBratney et al., 2006; Calderón et al., 2011; Janik et al., 2014) and soil-transfer factors for heavy metals (Wang et al., 2017). Several studies seem to indicate that soil clay mineralogy is a more appropriate soil parameter than the clay content for estimating the soil-plant transfer of radiocesium (Uematsu et al., 2015). Since the traditional XRD method for clay mineralogy analysis requires a quite laborious sample preparation, it is worthwhile to explore the capabilities of the MIR. Recently, a world-wide clay mineralogy map has been initiated by Ito and Wagai (2017). They created a geochemical dataset for the dominant (i.e. most abundant) clay-size mineral group present in the upper soil layer, based on a review of the clay mineralogy data from 27 papers. If this geo-referenced global dataset could be extended by more data from various regions, the map could be linked to a semi-mechanistic model for Cs, leading to improved predictions at spatial level.

Models at landscape level require large datasets of radiological, contamination, soil properties, land use, crops, etc. Large amounts of information can be gathered with the aid of further development and integration of existing measurement devices and techniques such as georeferenced sensors on board of satellites, manned and unmanned aerial vehicles, ground based vehicles or sensors integrated in in-situ networks such as those for air quality monitoring (Dunbabin and Marques, 2012; Bibri, 2018.

5.4. Priorities on risk management

There are large uncertainties involved in the management of the consequences of the accident. It is necessary to develop and implement better knowledge on countermeasures and new countermeasures strategies for the different phases (preparedness, response, transient and long term) and different geographical areas. This must include social, economic and ethical aspects.

Communication with stakeholders is a priority. It is crucial to find better ways to interpret the uncertainties of the impact assessment and to exchange information and engage stakeholders in the assessments and the decision making process, if one wishes to improve the radiological risk governance (Perko et al., 2019) and public well-being (Oughton, 2016). For example, although several process-based (semi-mechanistic) (models exist, these models have been rarely been used or implemented in decision support tools because such models are wrongly perceived by some stakeholders as being too complicated (Almahayni et al., 2019b). However, semi-mechanistic models are inherently easier to communicate to the stakeholders because they contain a representation of the system, unlike "black box" models based on simple partitioning ratios and assumptions, often derived by "expert judgement".

6. Conclusions

Decision support systems are an important instrument in the management of the food chain in case of a nuclear emergency. Depending on the phase of the emergency, the role of the DSS can change from guiding sampling and monitoring in the early phase to forecasting the feasibility and effectiveness of countermeasures for the food chain in the post-emergency phase. Models complement monitoring data and provide additional information when data are limited or not available. Nuclear emergencies are characterised by many uncertainties. Guidance by the experts on how to deal with the quantitative and qualitative uncertainties in the DSS is crucial for responsible decision-making.

Many of the radioecological models in DSS were developed for certain regions that have unique characteristics (e.g. environmental conditions, food production systems, human habits, etc.). Application of these models to different regions may require adjustment of their parameters or in certain cases re-parameterisation. The list of appropriate countermeasures, locally produced food products and environmental parameter values surely need to be adapted when used for other regions and research on this matter is ongoing. A lot of progress on data gathering and model capabilities has been made during the last decades. Recent developments in process-based models are now awaiting their implementation in the decision support tools. Future research on the modelling of the fate of radionuclides in the environment will involve, besides the improvement of the models, further experimental research on the parameters controlling the soil-plant transfer and also the foliar uptake, which has been less systematically studied. The fate of radionuclides at landscape level is also a priority, which will require more interdisciplinary research approaches and the application of new existing monitoring and analytical technologies and methods to map the radioactive contamination.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The Joint FAO/IAEA Programme on Nuclear Techniques in Food and Agriculture supported the preparation of this manuscript under CRP D1.50.15 on Response to Nuclear Emergency affecting Food and Agriculture. Any views expressed are not necessarily those of the IAEA.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvrad.2020.106444.

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