Environmental radiation protection – future challenges with regard to science and decision-making

C.-M. Larsson

Swedish Radiation Protection Authority, S-171 16 Stockholm, Sweden
E-mail: carl.magnus.larsson@ssi.se

Abstract. With Publication 91 on the impact of ionizing radiation on non-human species, the International Commission on Radiological Protection (ICRP) has taken a major step towards the integration of environmental issues into radiological protection. The conceptual framework has developed in response to public demand and concern for environmental issues, and is underpinned by technical development undertaken by several organisations at both national and international levels. The EC-funded FASSET project (Framework for Assessment of Environmental Impact), completed in 2004, has developed an assessment framework that includes: source characterisation and initial hazard analysis; ecosystem description and selection of reference organisms; exposure analysis including conversion to dose rates; effects analysis; and, guidance for interpretation. On the basis of experience from FASSET and other recent developments, it can be concluded that (i) there is substantial agreement in terms of conceptual approaches between different frameworks currently in use being or proposed, and that (ii) differences in technical approaches can be largely attributed to differences in ecosystems of concern or in national regulatory requirements. A major future challenge is the development of an integrated approach where decision-making can be guided by sound scientific judgements. This requires, inter alia: filling gaps in basic knowledge of relevance to assessment and protection, through targeted experimental, theoretical (including expert judgements) and real case studies; development of risk characterisation methodologies; development of screening standards, where appropriate; development of user-friendly assessment tools; and, stakeholder involvement, including the development of supporting communication strategies. These issues will be addressed in the ERICA project (Environmental Risks from Ionizing Contaminants – Assessment and Management) launched under the EC 6th Framework Programme during the spring 2004.

1. Introduction

Environmental radiation protection is, with the publication of ICRP Publication 91 [1], becoming an integral part of the international framework of radiological protection. This development has principally been driven by the necessity to update the ICRP recommendations and bring them into harmony with other assessment and management frameworks. This process has prompted an analysis of whether existing environmental protection methodologies and concepts can be applied within the field of environmental radiological protection. It has also stimulated efforts to organize existing knowledge on environmental transfer, exposure assessment including dosimetry, and effects, in a systematic fashion, i.e. into a ‘framework’, that enables assessments to be performed and that guides decision making. These ambitions are reflected in a number of international efforts [2, 3, 4, 5, 6, 7, 8].

The international efforts in this field include the FASSET project (Framework for ASsessment of Environmental impacts). FASSET was launched under the EC 5th Framework Programme in 2000 and terminated in early 2004. The project involved 15 organisations from seven European Countries (Finland, France, Germany, Norway, Spain, Sweden and UK). FASSET had the following practical objectives (see further [9, 10]):

i. to provide a set of reference organisms relevant to different exposure situations taking into account the environmental fate of radionuclide releases and exposure pathways;
ii. to provide a set of models for the reference organisms, including models for environmental transport of radionuclides, exposure, dosimetry and biological effects;
iii. to critically examine reported data on biological effects on individual, population and ecosystem levels, as a point of departure for characterizing the environmental consequences of, e.g., a source releasing radioactive substances into the environment; and,
iv. to review existing frameworks for environmental assessments used in different environmental management or protection programmes and, to the extent possible, draw on experience from these in creating a framework assessing the environmental impact of ionising radiation.

Also under the EC 5th Framework Programme, the EPIC project (Environmental Protection from Ionizing Contamination in the Arctic) worked under broadly the same general objectives as FASSET. EPIC involved four organizations in Norway, UK and Russia, and relied heavily on Russian data recently released to a wider scientific community. Although EPIC targets Arctic ecosystems, there are many commonalities between the projects, as reviewed by Larsson et al. [11] and Larsson and Strand [12].

This paper summarises FASSET’s achievements within the objectives specified above. The paper also highlights some outstanding issues being addressed within the ERICA project (Environmental Risks from Ionizing Contaminants – Assessment and Management), recently launched within the EC 6th Framework Programme.

2. FASSET output

All material produced within the FASSET project are publicly available at the project web-site, www.fasset.org. Table I summarises the major outputs.

<table>
<thead>
<tr>
<th>Output</th>
<th>Title</th>
<th>Editors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Appendix 1: Ecological characteristics of European terrestrial ecosystems. Overview of radiation exposure pathways relevant for the identification of candidate reference organisms (115 pp)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Appendix 2: Ecological characteristics of European aquatic ecosystems. Overview of radiation exposure pathways relevant for the identification of candidate reference organisms (79 pp)</td>
<td></td>
</tr>
<tr>
<td>Deliverable 2 (two reports), 2002</td>
<td>Part 1: Formulating the FASSET Assessment Context (77 pp)</td>
<td>Larsson, C.-M. Jones, C.</td>
</tr>
<tr>
<td></td>
<td>Part 2: Overview of programmes for the assessment of risks to the environment from ionising radiation and hazardous chemicals (84 pp)</td>
<td></td>
</tr>
<tr>
<td>Deliverable 3 (report), 2003</td>
<td>Dosimetric models and data for assessing radiation exposures to biota (103 pp)</td>
<td>Pröhl, G.</td>
</tr>
<tr>
<td></td>
<td>FASSET radiation effects database, FRED (CD)</td>
<td></td>
</tr>
<tr>
<td>Deliverable 5 (main report and two appendices), 2003</td>
<td>Handbook for assessment of the exposure of biota to ionising radiation from radionuclides in the environment (101 pp)</td>
<td>Brown, J. Strand, P. Hosseini, A. Borretzen, P.</td>
</tr>
<tr>
<td></td>
<td>Appendix 1: Transfer factors and dose conversion coefficient look-up tables (111 pp)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Appendix 2: Underpinning scientific information (life history sheets, empirical data and models) (183 pp)</td>
<td></td>
</tr>
</tbody>
</table>
3. Activities under the FASSET objectives

3.1. Objective (i) – setting reference organisms

Any impact assessment needs the identification of the object for which the impact should be estimated and evaluated. This represents a major problem in environmental radiological protection, considering the immense variability in species and within species. A certain simplification is necessary to allow assessments to focus on a few and ‘representative’ targets. The challenge is to identify a number of targets that is small enough to make assessments manageable without reducing the information value of the assessment. FASSET has dealt with this problem through developing the concept of ‘reference organisms’. This approach is analogous to the reference man concept adopted within radiological protection to provide a standard set of models and datasets. FASSET’s definition of the reference organism is: “a series of entities that provide a basis for the estimation of radiation dose rate to a range of organisms which are typical, or representative, of a contaminated environment. These estimates, in turn, would provide a basis for assessing the likelihood and degree of radiation effects”.

In order to identify the reference organisms, seven major European ecosystems have been characterized. These are for the terrestrial environment: semi-natural ecosystems including pastures, agricultural ecosystems, wetlands and forests; and for the aquatic environment: fresh-water, marine and brackish ecosystems.

The factors considered in the selection of reference organisms were: whether the habitat or feeding habits of the organism are likely to maximize its potential exposure to radionuclides; whether the organism exhibits radionuclide-specific bioconcentration; and whether the position of the organism within the foodchain (e.g., top predator) is such that biomagnification of radionuclides up the foodchain may lead to enhanced accumulation.

The approach taken towards their selection should ensure that suitable reference organisms are available for a range of scenarios (chronic and acute exposure) and for the different European ecosystems. In total, 31 candidate reference organisms have been chosen (Table II). It should be noted that these ‘organisms’ are not equivalent ‘real’ species – they rather represent biological components of vital importance for the functioning of the ecosystem, and thus become suitable targets for impact assessments. The reasoning behind the selection is given in Deliverable 1 (cf. Table I).

<table>
<thead>
<tr>
<th>Terrestrial ecosystems</th>
<th>Aquatic ecosystems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil</td>
<td>Sediment</td>
</tr>
<tr>
<td>Soil micro-organisms</td>
<td>Benthic bacteria</td>
</tr>
<tr>
<td>Soil invertebrates, ‘worms’</td>
<td>Benthic invertebrates, ‘worm’</td>
</tr>
<tr>
<td>Plants and fungi</td>
<td>Molluscs</td>
</tr>
<tr>
<td>Burrowing mammals</td>
<td>Crustaceans</td>
</tr>
<tr>
<td>Herbaceous layer</td>
<td>Vascular plants</td>
</tr>
<tr>
<td>Bryophytes</td>
<td>Amphibians</td>
</tr>
<tr>
<td>Grasses, herbs and crops</td>
<td>Fish</td>
</tr>
<tr>
<td>Shrubs</td>
<td>Fish eggs</td>
</tr>
<tr>
<td>Above ground invertebrates</td>
<td>Wading birds</td>
</tr>
<tr>
<td>Herbivorous mammals</td>
<td>Sea mammals</td>
</tr>
<tr>
<td>Carnivorous mammals</td>
<td>Water column</td>
</tr>
<tr>
<td>Reptiles</td>
<td>Phytoplankton</td>
</tr>
<tr>
<td>Vertebrate eggs</td>
<td>Zooplankton</td>
</tr>
<tr>
<td>Amphibians</td>
<td>Macroalgae</td>
</tr>
<tr>
<td>Birds</td>
<td>Fish</td>
</tr>
<tr>
<td>Canopy</td>
<td>Sea mammals</td>
</tr>
<tr>
<td>Trees</td>
<td></td>
</tr>
<tr>
<td>Invertebrates</td>
<td></td>
</tr>
</tbody>
</table>
3.2. **Objective (ii) – devising suitable models for various reference organisms**

A number of radionuclide transfer models developed for the seven major European ecosystems (see section 3.1), have been used for tabulation of external and internal radionuclide concentrations. Furthermore, calculations and tabulations have been made to allow conversion of external and internal concentrations to absorbed dose or dose rate. These tabulations have been published in Deliverables 3 and 5 (cf. Table I). These reports also contain estimates of natural background radiation for a number of ecosystems.

As an example of data generated under this objective, FIG. 1 presents the dose conversion factor for a mole that is exposed to a planar γ-source on top of the soil. The dose conversion factor increases in proportion to the γ-energy; it decreases with increasing soil depth separating the target from the source due to the increasing shielding effect of the overlying soil layer. The differences in shielding are more pronounced for low energies.

![Graph](image)

**FIG. 1.** Comparison of the dose conversion factors (DCF) for a mole as function of the γ-energy and the depth of the target for a homogeneous planar source at the top of the soil

3.3. **Objective (iii) - biological effects of ionizing radiation**

As far as current knowledge goes, radiation effects of ecological significance (changed population size and subsequent alteration in species composition) result from radiation damage at the sub-cellular level; there is no indication that radiation can directly affect higher organizational levels such as individuals or populations. Most radiotoxicity data on non-human species are available at the individual level with relatively less data on populations. Furthermore, individuals of numerous species are subject to protection by national or international law. It is therefore logical and justified to centre the effects analysis on individuals, accepting that effects must be observed in individuals before they can become manifested in the ecosystems. In order to organize the available knowledge on radiation effects, it was decided that FASSET would concentrate on four effects categories, or ‘umbrella effects’:

- morbidity (including growth rate, effects on the immune system, and the behavioural consequences of damage to the central nervous system from radiation exposure in the developing embryo);
• mortality (including stochastic effect of somatic mutation and its possible consequence of cancer induction, as well as deterministic effects in particular tissues or organs that would change the age-dependent death rate);
• reduced reproductive success (including fertility – the production of functional gametes, and fecundity – the survival of the embryo through development to a reproductive entity separate from its parents);
• mutation (induced in germ and somatic cells).

Deliverable 4 (cf. Table I) of the FASSET project reviews the current knowledge on radiation effects on biota, grouped under 17 wildlife groups. The report is supported by a database, the FASSET Radiation Effects Database (FRED). The database contains approximately 25,000 data entries from more than a thousand literature references, grouped according to wildlife group and umbrella effect. A particular reason for building the database was to facilitate derivation of dose-response relationships for different wildlife groups. However, this has proven to be possible only for mammals, fish and plants, and even in these cases such derivations should be performed with great caution. Users of the database are encouraged to read the original references identified in the FRED.

The reviewed data give few indications for readily observable effects at chronic dose rates below 100 microGy per hour. However, for a number of reasons, it is advised that using this information for establishing environmentally ‘safe’ levels of radiation should not be done considering that:

• the database contains large information gaps for environmentally relevant dose rates and ecologically important wildlife groups; and,
• relative biological efficiencies of e.g. alpha-emitters, and resulting weighting factors, for environmentally relevant endpoints are ill characterized.

With reference to the latter point, the FRED contains only very limited information that enable derivation – or even discussion – of appropriate weighting factors. Under conditions where total radiation levels are low, and/or the contribution from alpha emitters is small, and/or where uncertainties in radionuclide transfer introduces a much higher element of uncertainty, the weighting factor may play a minor role in the result of the assessment. The recommendation is that assessors, as a part of a sensitivity analysis, make a judgment whether the weighting factor matters in each particular case.

3.4. Objective (iv) - framework issues

The general structure of existing frameworks for environmental risk assessment has been considered to be appropriate also for FASSET; i.e., a division of the assessment into five separate steps: planning, formulation of the assessment context, assessment, risk characterization, and decision and management. The separation into these steps is a common feature of a number of existing ‘systems’ for both radiological and non-radiological hazards - as reviewed, compared and synthesized in Deliverable 2 (cf. Table I), although all systems may not comprise all five steps.

Only the formulation of the assessment context (Deliverable 2) and the assessment steps were covered by the FASSET project and are included in the framework. Risk characterization and managerial issues were not covered. However, these steps will be addressed within the ERICA project, as further described in section 4 of this paper.

The sequence of the assessment, as outlined in the FASSET framework, is given in Table III, together with reference to the supporting tools and documentation, as well as an indication as to where the new ERICA project will extend the framework.
Table III. Sequence, supporting tools and documentation for impact assessments following the FASSET framework. D (Deliverable) and FRED refer to the FASSET Deliverables listed in Table I.

<table>
<thead>
<tr>
<th>No.</th>
<th>Step</th>
<th>Procedure</th>
<th>Example</th>
<th>FASSET tools</th>
<th>FASSET Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Assessment context Source and hazard characterisation</td>
<td>Make initial prioritisation based on released amount, and taking physical, chemical and biological characters of relevant radionuclides into account</td>
<td>Cs-137, Sr-90…</td>
<td>• Radionuclides of 20 elements included in FASSET&lt;br&gt;• Overview of initial hazard analysis</td>
<td>D1, D2</td>
</tr>
<tr>
<td>2</td>
<td>Assessment context Ecosystem characterisation</td>
<td>Identify the affected ecosystem, define the spatial and temporal boundaries</td>
<td>Brackish waters, forests…</td>
<td>• Detailed ecosystem descriptions for four terrestrial and three aquatic European ecosystems</td>
<td>D1</td>
</tr>
<tr>
<td>3</td>
<td>Assessment context Reference organism selection</td>
<td>On the basis of input from steps 1 and 2, select appropriate reference organism for further consideration</td>
<td>Tree, pelagic fish…</td>
<td>• Selection, on ecosystem and exposure basis, of reference organisms.&lt;br&gt;• Development of reference geometries for the above&lt;br&gt;• Life history data for representative examples within the reference organism definition</td>
<td>D1, D3, D5</td>
</tr>
<tr>
<td>4</td>
<td>Assessment Exposure analysis</td>
<td>Using the input from steps 1 – 3, estimate external, and internal radionuclide concentrations and exposure</td>
<td></td>
<td>• Transfer models and compilation of radionuclide concentrations&lt;br&gt;• Dose conversion factors</td>
<td>D3, D5</td>
</tr>
<tr>
<td>5</td>
<td>Assessment Effects analysis</td>
<td>Using dose (rate) data from step 4, screen against effects database to determine the likely degree of effect for selected umbrella effects</td>
<td>Mortality, reproductive success…</td>
<td>• Database&lt;br&gt;• Guide to data evaluation</td>
<td>FRED, D4</td>
</tr>
<tr>
<td>6</td>
<td>Risk characterisation</td>
<td>Identify level of concern taking into account uncertainties, perform sensitivity analysis</td>
<td>Insignificant, high…</td>
<td>• General advice</td>
<td>D 4, D 6, ERICA</td>
</tr>
<tr>
<td>7</td>
<td>Decision and management</td>
<td>Evaluate the risk profile against legal requirements in stake-holder dialogue</td>
<td>Approve, decline, intervene…</td>
<td>Outside scope of FASSET</td>
<td>ERICA</td>
</tr>
</tbody>
</table>

4. Way forward – the ERICA project

On the basis of experiences from FASSET, and other recent projects, it can be concluded that:

- there is substantial agreement in terms of conceptual approaches between different frameworks currently in use or proposed; and,
- differences in technical approaches can largely be attributed to the differences between ecosystems of concern, or to different national legal requirements.
A major future challenge is the development of an integrated approach where decision-making can be guided by sound scientific judgements. This requires, *inter alia*:

- filling of gaps in basic knowledge of relevance to assessment and protection, through targeted experimental, theoretical (including expert judgements) and real case studies;
- development of risk characterisation methodologies, based on both theoretical and experimental studies and incorporating a rationale for extrapolation of effects data;
- development of screening standards, where appropriate;
- development of user-friendly assessment tools; and
- stakeholder involvement, including development of supporting communication strategies.

As mentioned earlier, some of the outstanding issues will be addressed within the EC 6th Framework Programme project ERICA, launched during the spring 2004. The objective of ERICA is to provide an integrated approach to scientific, managerial and societal issues concerned with the environmental effects of contaminants emitting ionising radiation, with emphasis on biota and ecosystems. The final outcome of the project will be the ERICA *integrated approach to assessment and management of environmental risks from ionising radiation*, using practical tools.

The objective will be fulfilled through development of a user-friendly assessment tool with risk characterisation methodologies coupled with communication strategies aimed at decision-making. This involves detailed consideration of gaps in scientific data, expansion of the current effects database, and experimental and theoretical consideration of extrapolation issues, e.g. from effects on individuals to effects on populations. The tool will be tested and applied to a series of case studies. The development of science-based managerial guidance, including methodologies for stakeholder involvement in assessments, will be based on a number of meetings with end-users representing a range of different interests (the ‘End Users Group’, EUG), whom have agreed to participate in ERICA.

The project is organised in five different work packages (WPs), out of which work package 5 is entirely devoted to project management and progress assessment. The content of the four operative work packages is briefly described in the following.

**4.1. WP1 – Assessment tool**

The tasks of WP1 are to develop the ERICA assessment tool and in doing this also bridge knowledge gaps and quantify data uncertainties, focusing on:

- environmental radionuclide transfer;
- dosimetry;
- dose-effect relationships; and,
- development of the assessment tool.

A ‘FREDERICA’ effects database will be developed within the project based on the FRED and EPIC databases. Actions include: a merging of the FRED database with the EPIC database, and insertion of data from post 2001 articles; inclusion of a limited number of specific experimental data which will be carried out within the ERICA project; and a new output structure for the ERICA database providing more flexible search options. The assessment tool will integrate environmental radionuclide transport, bioaccumulation, dosimetry, and radiation-effect assessment in a comprehensive, flexible and user-friendly manner. Commonly available Windows software supplemented by the modelling software package *Ecoligo* [13] will be used as a basis for development of the tool.

**4.2. WP2 – risk characterisation**

Risk characterisation may be defined as ‘the synthesis of information obtained during risk assessment for use in management decisions’, and will be an important element in the ERICA integrated...
approach, as the risk characterisation will guide societal and managerial perceptions, prioritisations and actions. WP 2 will consider:

- risk characterisation methodologies;
- extrapolation issues including supporting experimentation; and,
- development of good practice guidance.

The quantification of the main sources of uncertainties associated with safe/acceptable criteria will be derived, *inter alia*, through experimentally-acquired weight of evidence. Extrapolation issues will be considered theoretically and experimentally, e.g. extrapolation of effects data from populations to ecosystems level, and extrapolation of observations from single-radionuclide exposures to a multicontaminant environment. Lessons learnt from experiments on some test organisms, combined with literature information on standard ecotoxicological bioassays, will be used to discuss and make recommendations for using some of these tests in the assessment of radionuclide effects. To some extent, this review will be complemented by good laboratory practice criteria that should be applied to obtain quality laboratory data concerning effects.

4.3. WP – decision making involving stakeholder issues

The task of WP3 is to develop managerial guidance together with stakeholder methodologies, in order to protect the environment from ionising radiation. The activities of this WP can be grouped into three broad categories:

- the set-up and consolidation of the EUG;
- consultation activities; and
- guidance and training.

Following consolidation of the EUG, consultations will be arranged as a number of meetings, involving different expertise from the EUG as well as from the project consortium. Consultations will focus on: identification of key information needs for setting criteria and standards, based on experiences from the FASSET project and other activities; reaching consensus in areas of significant scientific uncertainties; management, demonstration and compliance; and, as a special case, a dialogue involving local stakeholders in the UK case study. Towards the end of the project, a workshop will be organised to demonstrate to end-users how the assessment system developed within the framework can be practically applied.

4.4. WP4 – case studies

The task of WP4 is to apply and develop methodologies in practical cases, to facilitate the development of the ERICA integrated approach. This will be performed in two major phases:

- testing and evaluation of the FASSET framework at each site; and,
- testing the ERICA software prototype at each site to allow refinement of the ERICA integrated approach.

A variety of sites with different discharge histories (routine anthropogenic, accidental anthropogenic, technologically-enhanced natural) and ecosystems are required to ensure that the various aspects of this work package can be addressed. The sites that have been selected are:

- Sellafield (UK) - Routine aerial and marine releases from Sellafield have resulted in estuarine and terrestrial contamination with a wide range of different radionuclides to comparatively high levels. In particular, coastal salt marshes contain high levels of a range of alpha emitters.
- Loire River (France) - The Loire River receives routine discharges from nuclear power plants. This case study provides the opportunity to test the freshwater and brackish components of FASSET/ERICA.
The Chernobyl exclusion zone (Ukraine) - The zone provides a site where radiation induced effects have been observed for anthropogenic sources, enabling effect predictions to be assessed.

Oil rigs (North-East Atlantic) - Estimates of input of radioactive substances into the marine environment suggest that the European offshore oil industry is a significant source of alpha-emitting radionuclides.

Komi Republic (Russia) - This is an area of high natural radioactivity where radiation induced effects have been reported.

5. Concluding remarks

It is apparent from this overview and work cited in section 1 that environmental radiological protection is rapidly developing. The development of assessment frameworks for environmental radiation, that are similar to those used for other hazardous substances, facilitates communication and exchange of experience across broad areas of environmental issues. However, so far relatively little has happened in terms of policy development. The rate by which environmental radiation may become part of policies depends to some extent on how the ICRP will integrate the content of Publication 91 [1] into its forthcoming general recommendations, due 2005. The ERICA project, as well as other recent and ongoing activities, may further support policy development by supplying underpinning scientific knowledge, assessment frameworks and tools, as well as decision-making guidance.

6. Acknowledgements

This work was supported by, and forms part of, the EC FASSET (Framework for Assessment of Environmental Impact) project, FIGE-CT 2000-00102. The author would like to acknowledge the input from all team members within the organizations that make up the FASSET Consortium:

Swedish Radiation Protection Authority
Swedish Nuclear Fuel and Waste Management Co.
Kemakta Konsult AB, Sweden
Stockholm University, Sweden
Environment Agency (UK)
Centre for Ecology and Hydrology, UK
Westlakes Scientific Consulting Ltd, UK
Centre for Environment, Fisheries and Aquaculture Sciences, UK
University of Reading, UK
German Federal Office for Radiation Protection
German National Centre for Environment and Health
Spanish Research Centre in Energy, Environment and Technology
Radiation and Nuclear Safety Authority, Finland
Norwegian Radiation Protection Authority
Institut de Radioprotection et de Sûreté Nucléaire, France

7. References


