FASSET

Framework for Assessment of Environmental Impact

Deliverable 6

Framework for assessment of environmental impact of ionising radiation in major European ecosystems

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FASSET brings to radiation protection a framework for the assessment of environmental impact of ionising radiation. The framework links together current knowledge about sources, exposure, dosimetry and environmental effects/consequences for reference organisms and ecosystems. Relevant components of the framework have been identified on an ecosystem basis through systematic consideration of the available data. The application of the framework in assessment situations is described in this, the final, report from the project.

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Executive summary

Introduction

The FASSET project was launched in November 2000, under the EC 5th Framework Programme, to develop a framework for the assessment of environmental impact of ionising radiation in European ecosystems. It involved 15 organisations in seven European countries and set out to organise radioecological and radiobiological data into a logic structure that would facilitate the assessment of likely effects on non-human biota resulting from known or postulated presence of radionuclides in the environment. The project included an overview of 20 pathway-based environmental assessment systems targeted either to radioactive substances, or hazardous substances in general.

The resulting FASSET Framework includes the following fundamental elements: source characterisation; description of seven major European ecosystems; selection of a number of reference organisms on the basis of prior ecosystem and exposure analysis; environmental transfer analysis; dosimetric considerations; effects analysis; and, as an integral part of the aforementioned steps, general guidance on interpretation, including consideration of uncertainties and possibilities to extrapolate from existing data to areas where data are absent or scarce. The project has used existing information, supplemented by the development of models, by performing Monte Carlo calculations to derive dose conversion factors, and by building an effects database (FRED, the FASSET Radiation Effects Database).

The project has delivered six scientific reports, or Deliverables, D1-D6. The present and final report on the FASSET Framework, D6, describes the Framework and integrates specific components from the previous five deliverables. All documentation from FASSET can be found on the web-site, www.fasset.org.

Framework overview

The FASSET framework is described below, and is illustrated in Figure 1, which also highlights the structure of the present report.

Source characterisation

The initial phase of the assessment involves the characterisation of the radionuclide input in the environment. A set of radionuclides from 20 elements was selected for inclusion within the Framework, on the basis of being routinely considered in assessments and emergency planning for accidental releases; representing a range of environmental mobilities and biological uptake rates; being of both anthropogenic and natural radionuclides; and, being representatives of α-, β- and γ-emitters [D1].

Furthermore, a preliminary flowchart for the screening of radionuclides and a description of criteria useful in the process has been described. This guidance was based on a number of criteria used to define the source term, physical characteristics, environmental fate, biological activity and chemical characteristics, as discussed in [D2].

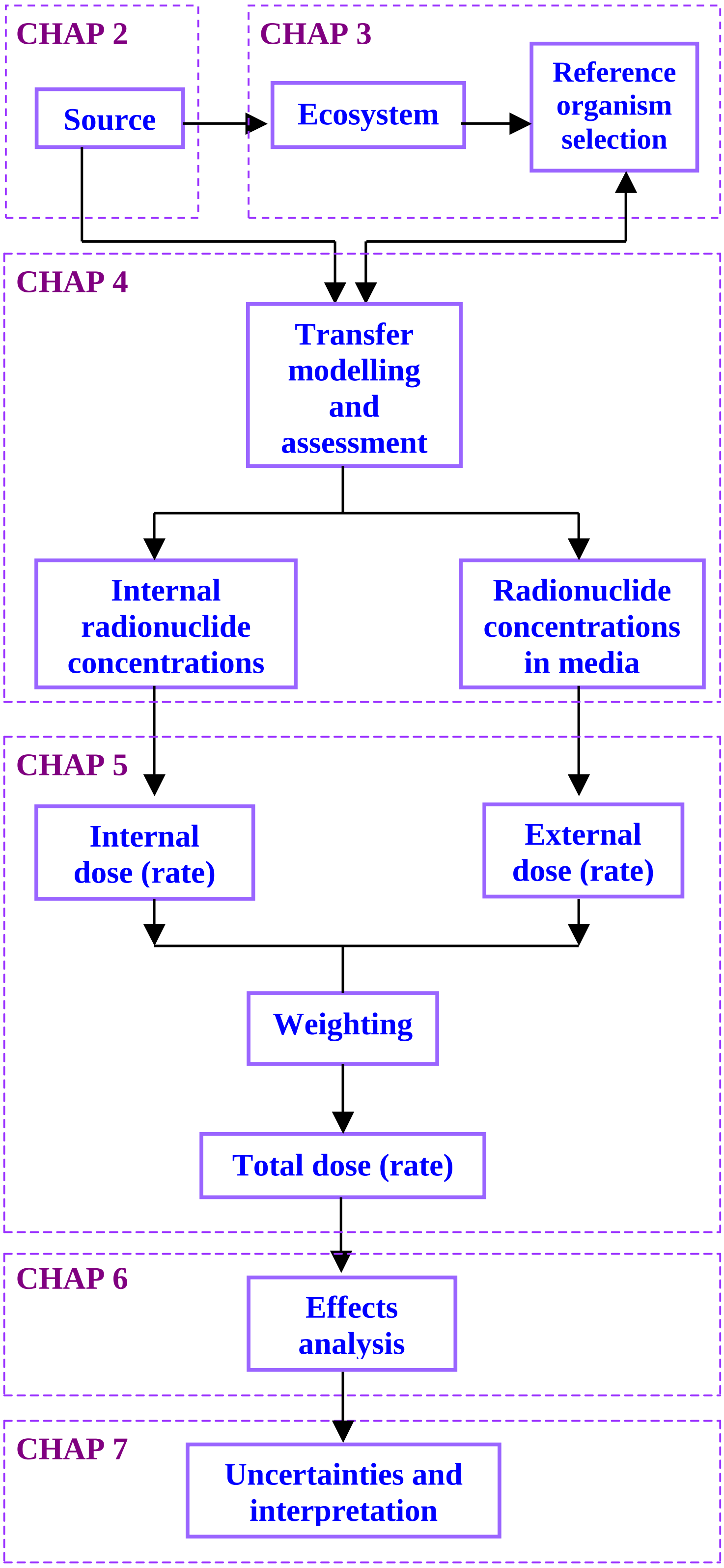

Figure 1 Sequential organisation of the Framework elements, as developed by the FASSET Project, with reference to the chapters in this D6 report.

Ecosystem characterisation and selection of 'reference organisms'

The Framework includes information on seven European ecosystems to allow for identification of maximally exposed ecosystem components [D1]. The ecosystems considered were as follow.

- *Forests*: land with tree crown cover of more than 10 %, an area of more than 0.5 ha and with trees, which are able to reach a minimum *in situ* height of 5 m at maturity.
- *Semi-natural pastures and heathlands*: including mountain and upland grasslands, heath and shrub lands, saltmarshes and some Arctic ecosystems.
- *Agricultural ecosystems*: including arable land, intensively managed pastures and areas used for fruit production.
- *Wetlands*: areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish, or salt.
- *Freshwaters*: all freshwater systems, including rivers and lakes.
- *Marine*: the North-Eastern section of the Atlantic Ocean and its marginal seas.
- *Brackish waters*: the non-tidal, shallow Baltic Sea; organisms are immigrants from either marine or freshwater systems.

The ecosystems overview led to identification of a number of reference organisms, based on habitat and feeding habits, as well as bioaccumulation and biomagnification [D1]. The Framework defines the reference organism as: *"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 total, *ca* 30 reference organisms have been chosen. It should be noted that these 'organisms' are not equivalent to specific species – they rather represent biological components of importance for the functioning of each ecosystem, and thus they are suitable targets for impact assessments.

Environmental transfer and dosimetry

A number of radionuclide transfer models developed for the seven major European ecosystems have been used for calculation of external and internal radionuclide concentrations. Furthermore, calculations and tabulations have been made to allow conversion of external and internal concentrations to absorbed dose (rate), including dose rates resulting from natural background radiation for a number of ecosystems. The Conversion factors for estimates of dose rates have involved Monte Carlo calculations and the definition of a number of representative geometries for different reference organisms. Data have been compiled in a Handbook on the initial assessment stages [D5], as well as in a separate report on dosimetry [D3].

Effects analysis

The Framework centres the effects analysis on individuals, accepting that effects must materialise in individuals *before* they can become manifested within the ecosystems. In order to organise the available knowledge on radiation effects, it was decided that the Framework 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 and fecundity).
- *Mutation* (induced in germ and somatic cells).

[D4] reviews the current knowledge on radiation effects on biota, grouped under 16 broad wildlife groups, which are broadly comparable with the chosen reference organisms. The report is supported by the FASSET Radiation Effects Database (FRED). The database contains approximately 25 000 data entries from more than a thousand references. The reviewed effects data give few indications of readily observable effects at chronic dose rates below 100 µGy/h. However, it is advised that using this information for establishing environmentally ‘safe’ levels of radiation should be done with caution, considering that the database contains large information gaps for environmentally relevant dose rates and ecologically important wildlife groups. Assessors are encouraged to use the database as a starting point, and seek the original papers to extract more detailed information.

The FRED contains only limited data that enable the derivation – or even discussion – of radiation weighting factors. The recommendation is that assessors, as a part of a sensitivity analysis, make a judgment whether the weighting factor matters in each particular case.

Uncertainties and interpretation

The Framework contains general advice as to the interpretation and handling of uncertainties associated with the assessment. For a number of radionuclides, transfer and effects data are lacking or scarce, necessitating information to be extrapolated from ‘known’ data, and involving a substantial component of expert judgment.

Outlook

On the basis of the FASSET experience, 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 that differences in technical approaches can largely be attributed to the differences between ecosystems of concern, or to different national legal requirements. Furthermore, sufficient knowledge appears to be available to support robust, scientifically-based assessments following the FASSET framework structure, although significant data gaps exist, *e.g.* concerning environmental transfer of key nuclides and effects data for key wildlife groups at environmentally relevant dose rates.

Future challenges lie in the development of an integrated approach where decision-making can be guided by sound scientific judgements, which requires, *inter alia*: filling of gaps in basic knowledge of relevance to assessment and protection; development of risk characterisation methodologies; development of user-friendly assessment tools; and stakeholders involvement, including the development of supporting communication strategies.

Some of the above outstanding issues will be addressed within the EC 6th Framework Programme project ERICA (Environmental Risk from Ionising Contaminants: Assessment and Management), which was launched in March 2004 and takes the FASSET framework as its starting point. 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 has been termed the ERICA integrated approach to assessment and management of environmental risks from ionising radiation. Progress of the ERICA project can be followed on the web-site, www.erica-project.org.

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1 Development of the Framework – general background

Introduction

This report presents an overview of the Framework for Assessment of Environmental Impact (FASSET) of ionising radiation, developed under the EC 5th Framework Programme. Work commenced in November 2000 and this report constitutes the sixth and final scientific report from the project.

The FASSET project became part of the EC 5th Framework Programme at a time when a number of international efforts within radiological sciences and protection were directed towards environmental issues. This trend was not generated by any particular concern that major radiological impact in the environment could have been overlooked. It rather reflected a desire by society to include the radiological impact on the environment in environmental impact assessments (EIA), to facilitate interaction with so-called stakeholders during the EIAs and to provide a more holistic view of protection where radiation is but one of a multitude of actual and potential hazards or risks to the environment created by human actions.

The change in societal view was at the time not matched by internationally agreed guidelines or recommendations. On the contrary, the main international body assigned the authority to issue such recommendations, the International Commission on Radiological Protection (ICRP), was itself *reacting* to the changed view rather than taking the initiative to bring this change along. With the recent Publication 91 on the impact of ionising radiation on biota [ICRP 2003], however, the Commission has taken a major step towards integration of environmental issues in its forthcoming general Recommendations, due 2005.

The major international body within the nuclear field, the UN International Atomic Energy Agency (IAEA), develops radiation safety standards to assist its Member States in implementing the ICRP Recommendations within the nuclear field. The Agency has organised a series of technical meetings and major conferences (*e.g.* the International Conference on the Protection of the Environment from the Effects of Ionizing Radiation, Stockholm, October 2003) in this area, and is – against the background of the ongoing revision of the ICRP Recommendations – developing an action plan for reviewing and, as appropriate, revising its standards, for consideration by the IAEA Member States.

In the earlier absence of an ICRP position, and other internationally agreed guidance, a number of technical and scientific developments have taken place to build assessment frameworks, including current work within ICRP and IAEA [Copplestone *et al*., 2001; Higley *et al.*, 2001; Strand and Larsson, 2001; Pentreath and Woodhead, 2001; Thompson and Chamney, 2001; Holm, 2002; IAEA 2002, ICRP, 2003]. A number of these have been reviewed and compared within the FASSET project, along with other systems for assessment and management of non-radioactive hazardous substances, see **[D2:1]**[1] and **[D2:2]**. From the overview, it became evident that the basic structure of existing frameworks was analogous and contained (see Figure 1-1):

[1] See Section 1.3 and Tables 1-1 and 1-2 for explanation of the system for referring to FASSET documentation

- a planning stage, where any planned activity is assessed against the legal background;
- a problem formulation stage, where the approach towards the assessment is defined;
- an assessment stage, where the actual analysis of exposure and effects is made;
- a risk characterisation stage, where the aspects of concern are defined taking into consideration that radiation is but one of potentially several environmental hazards associated with a source of radiation; and,
- a decision stage, where risk-informed decisions are taken, supported by previous stages of the assessment and in communication with those that have a say in the decision-making, usually referred to as stakeholders.

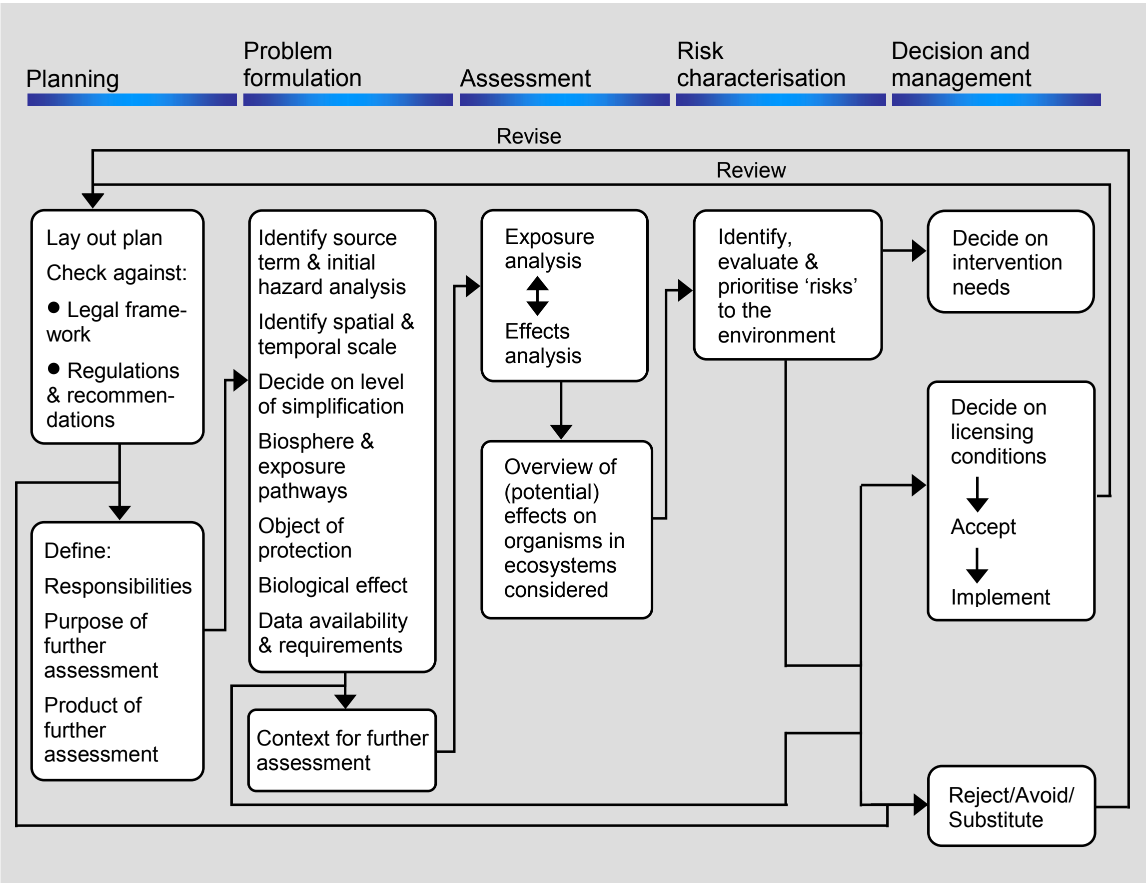

Figure 1-1 Elements of a 'generic' framework for impact assessment and management of hazardous substances, including radionuclides, based on a systems overview performed within FASSET.

The review was part of the objectives (see further below). At the same time it greatly facilitated the development of a framework that would be coherent with others, addressing comparable environmental hazards or risks. The advantages with such coherence is substantial and allows for:

- drawing on experiences from other frameworks across a wide range of environmental areas; and,
- facilitating stakeholder dialogues by enabling a common language to be used for a variety of environmental hazards handled within an EIA.

Still, there are peculiarities to radioactive substances that require special attention or methodological development that have been dealt with in FASSET and elsewhere.

1.1 Objectives of the FASSET project

FASSET had the following practical objectives, as further explained and elaborated in the Technical Annex to the project **[TA]**:

- to provide a set of reference organisms relevant to different exposure situations taking into account the environmental fate of radionuclide releases and exposure pathways;
- to provide a set of models for the reference organisms, including models for environmental transport of radionuclides, exposure, dosimetry and biological effects;
- 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,
- 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 Ionising Contamination in the Arctic) worked broadly under the same general objectives as FASSET. EPIC involved four organisations in Norway, UK and Russia, and relied heavily on Russian data recently released to a wider scientific community. Although EPIC targeted Arctic ecosystems, there were many commonalities between the two projects, as reviewed by Larsson *et al.* [2002] and Larsson and Strand [2004], and in the final report from the project [Brown *et al.*, 2003].

Whilst addressing the objectives formulated above, it was also necessary at an early stage to define the scope of the Framework. This was done in a systematic fashion, building on the documentation available from the IAEA Biosphere Modelling and Assessment (BIOMASS) project [IAEA, 2003], and discussed during a FASSET workshop in 2001 **[FASS/BIOM]**, as well as during the FASSET External Forum **[ExtFor]**.

In summary, decisions were taken on the following aspects of the assessment context:

- *purpose* – to present an estimate of environmental impact that is as realistic as possible, while still using general or generic information, to guide decision-making;
- *source term and hazard identification* – to be flexible in terms of sources, environmental properties, and effects of different nuclides, and to provide a means to prioritise;

- *spatial and temporal scale* – to consider acute and chronic exposures for the relevant environment;
- *biosphere and level of simplification* – to use generalised data for seven European ecosystems (three aquatic and four terrestrial), and to use a set of 'reference organisms' as basis for impact analysis;
- *object of protection* – there may be cases where the object is predefined through legislation, *i.e.*, in the case of rare and/or endangered species. In other cases, objects of protection may be identified on their significance to ecosystem function, exposure situation and sensitivity to radiation, and often using multiple criteria. The 'reference organism' approach will assist in making these judgements.
- *effects* – to compile and assemble in a database information on effects of ionising radiation on different wildlife groups, organised in four 'umbrella' categories, morbidity, mortality, reproductive success, and mutation, as a basis for estimating impact on individuals;
- *data requirements and availability* – to use 'realistic' data if available and extrapolate with reasonable caution when data are missing.

1.2 Overview of FASSET documentation underpinning the Framework

This report can be read as a stand-alone, in the sense that it introduces the reasoning behind the development of the Framework, and reviews its components and application. However, any user of the Framework may wish – and is indeed encouraged – to consider the technical content in detail, as it is presented in the other five FASSET deliverables, which precede this report and underpin the Framework.

Table 1-1 summarises the technical reports delivered by the FASSET project. All these are available from the website (www.fasset.org). Throughout this report, reference will be made to other FASSET deliverables as well as to other Chapters in this report; *e.g.* reference to **[D1:App.2, 3]** will guide the reader to Deliverable 1, Appendix 2, Section 3. The reference system is further explained in Table 1-1. For readers of the CD version or on the Internet, clicking on the reference will actually access it.

Other documentation of relevance to the development of the FASSET Framework is summarised in Table 1-2. This includes the original project work plan, which describes the underlying understanding of the situation at the start of the project, and minutes from two consultations. The latter of the two, the FASSET External Forum held in Bath UK, April 2002, was significant in that it allowed the project to consider and, as appropriate, take on board a number of recommendations made by 'stakeholders' from outside the FASSET consortium, representing widely different backgrounds, attitudes and responsibilities within the field.

Table 1-1 Technical outputs from the FASSET project, available at www.fasset.org.

Output	Title	Identifier in this report	Editors
Deliverable 1 (main report, and two appendices), 2001	Identification of reference organisms from a radiation exposure pathways perspective (48 pp)	[D1]	Strand, P. Beresford, N. Avila, R. Jones, S.R. Larsson, C.-M.
	Appendix 1: Ecological characteristics of European terrestrial ecosystems. Overview of radiation exposure pathways relevant for the identification of candidate reference organisms (115 pp)	[D1:App.1]	
	Appendix 2: Ecological characteristics of European aquatic ecosystems. Overview of radiation exposure pathways relevant for the identification of candidate reference organisms (79 pp)	[D1:App.2]	
Deliverable 2 (two reports), 2002	Part 1: Formulating the FASSET Assessment Context (77 pp)	[D2:1]	Larsson, C.-M. Jones, C.
	Part 2: Overview of programmes for the assessment of risks to the environment from ionising radiation and hazardous chemicals (84 pp)	[D2:2]	
Deliverable 3 (report), 2003	Dosimetric models and data for assessing radiation exposures to biota (103 pp)	[D3]	Pröhl, G.
Deliverable 4 (report and database), 2003	Radiation effects on plants and animals (196 pp)	[D4]	Woodhead, D. Zinger, I.
	FASSET radiation effects database, FRED (separate deliverable under D4)	[FRED]	
Deliverable 5 (main report and two appendices), 2003	Handbook for assessment of the exposure of biota to ionising radiation from radionuclides in the environment (101 pp)	[D5]	Brown, J. Strand, P. Hosseini, A. Borretzen, P.
	Appendix 1: Transfer factors and dose conversion coefficient look-up tables (111 pp)	[D5:App.1]	
	Appendix 2: Underpinning scientific information (life history sheets, empirical data and models) (183 pp)	[D5:App.2]	
Deliverable 6 (report), 2004	Framework for assessment of environmental impact of ionising radiation in major European ecosystems (70 pp)	[D6]	Larsson, C.-M. Jones, C. Gomez-Ros, J.M. Zinger, I.

Table 1-2 Supporting documentation available at www.fasset .org

Documentation	Title	Identifier in this report
Project work plan	FASSET Technical Annex	**[TA]**
Minutes	FASSET/BIOMASS workshop, Stockholm, October 2001	**[FASS/BIOM]**
Minutes	FASSET External Forum, Bath, April 2002	**[ExtFor]**

1.3 Structure of this report

This report's subsequent Chapters review the Framework elements, provide a number of observations relevant to the application and associated uncertainties of different Framework tools, and give reference to the detailed documentation as listed in Tables 1-1 and 1-2.

The chapters follow the sequence of the assessment framework, as schematically presented in Figure 1-2. Consideration is given to:

- source characterisation **[D6, 2]**;
- characteristics of the receiving and/or affected ecosystems and appropriate reference organisms **[D6, 3]**;
- ecological radionuclide transfer to estimate radionuclide concentrations in environmental media and in organisms **[D6, 4]**;
- dosimetry and exposure assessment **[D6, 5]**;
- effects analysis **[D6, 6]**; and
- preliminary information on interpretation of assessment data **[D6, 7]**.

The planning stage (*cf*. Figure 1-1), including the initial screening against the legal framework, is outside the scope of the Framework, and it rests with users to apply the Framework within their national legal environment. Risk characterisation is also outside the scope, although some advice is given. Finally, decision and management can be informed by the impact assessment, although the Framework does not *per se* include methodologies directed specifically at decision-making.

Each of the following chapters introduce the specific Framework component dealt with, indicate sources of information and available tools in underpinning Framework documentation, and make general observations and recommendations based on the FASSET experience.

For definition of terms used in the framework, consult glossaries in **[D2:1 App.2]** and **[D5, page 11 – 16]**.

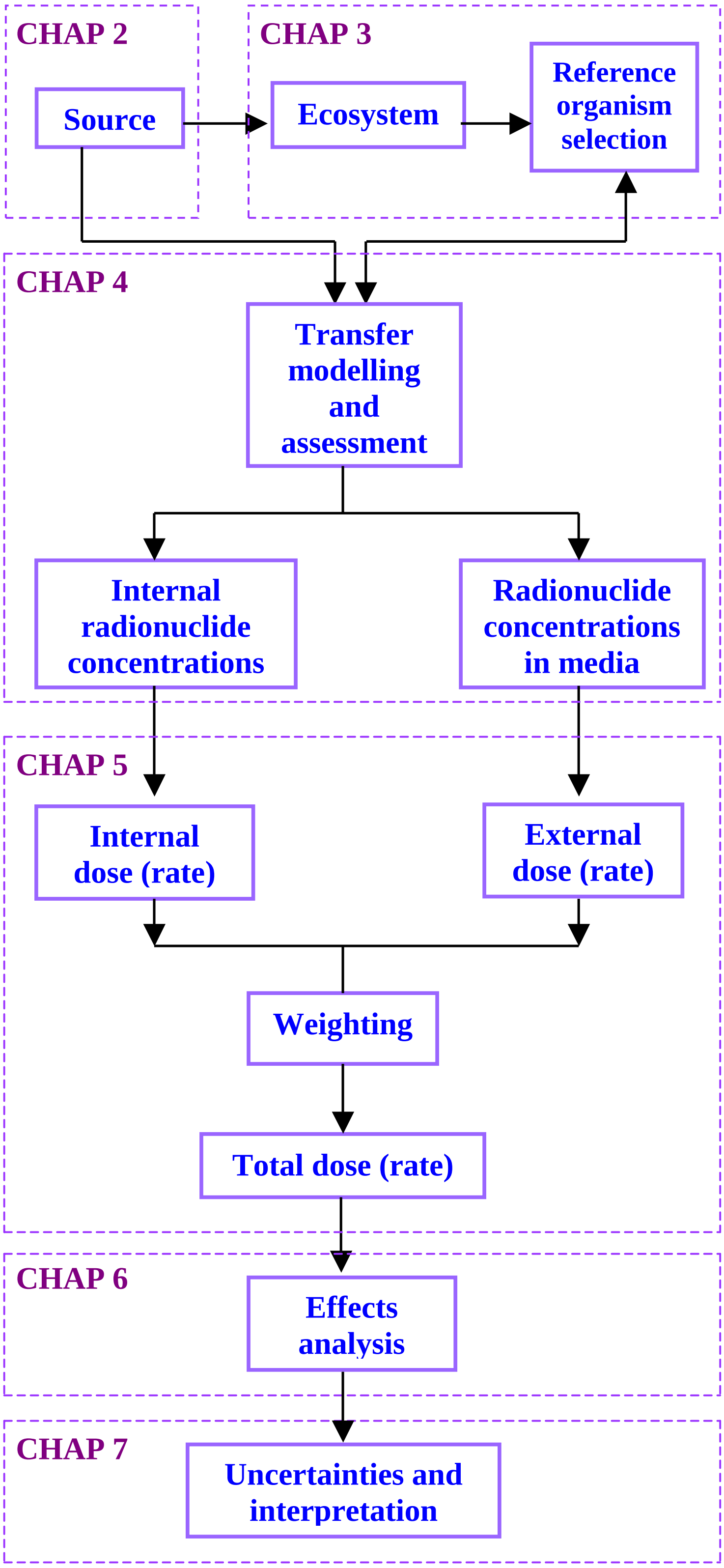

Figure 1-2 Sequential organisation of the Framework elements, as developed by the FASSET Project, with reference to the chapters in this D6 report.

2 Source characteristics

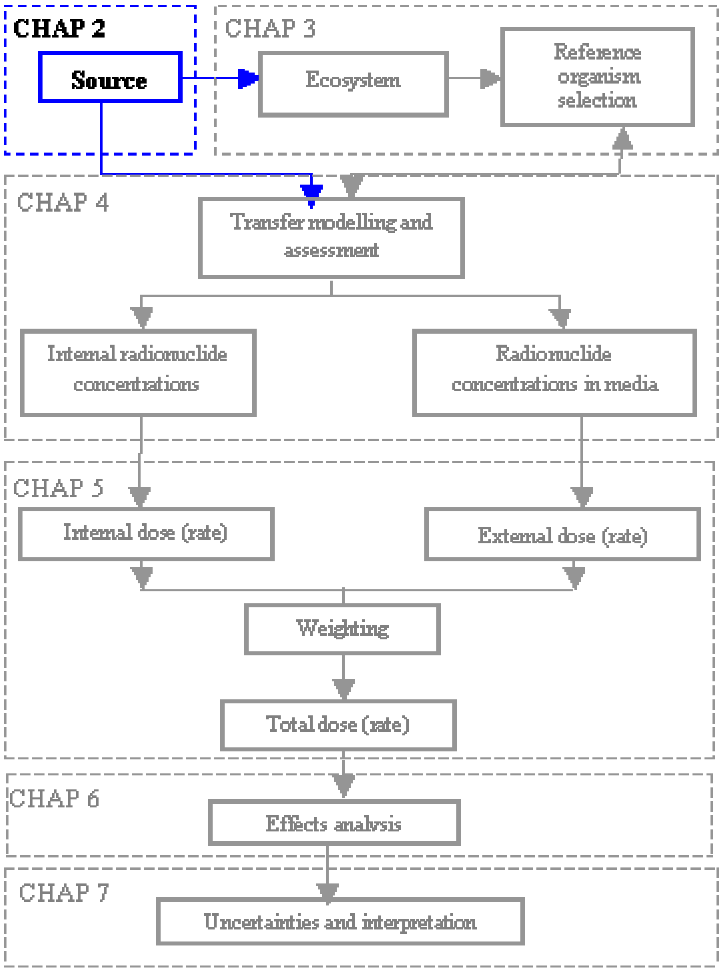

Figure 2-1 Position of the source characterisation within the Framework.

2.1 Introduction

Within frameworks of ecological risk assessments, substances requiring further analyses and assessments are normally selected on the basis of their persistence, the likelihood of them being transported over long distances, and their potential for bioaccumulation and environmental effects. Applied to ecological risks of ionising contaminants, the initial phase of the assessment involves the characterisation of (i) the nature of the radionuclide input into the environment (the source characteristics) and (ii) the nature of the receiving environment (ecosystem characterisation, see further **[D6, 3]**), as indicated in Figure 2-1. A screening methodology could be applied to results from the initial source characterisation, in order to determine whether a further assessment is needed (if initial screening deems risks being trivial or unacceptable no further assessment may be needed) or, in the case further assessment is deemed necessary, to decide on the level of detail and the product of the assessment. Note that legal requirements may bypass any such considerations and call for no assessment (*e.g.* planned activity is illegal, or the source is excluded or exempt from regulatory control) or may state that full assessment without prior screening analysis is necessary.

2.2 Overview of Framework information and tools

Relevant Framework information on source term characterization is described in supporting FASSET documentation as follows:

- a sub-set of radionuclides was selected for use in the collation of data and the development of Framework tools **[D1]** as presented in Table 2-1; and,
- a preliminary guideline for the screening of radionuclides for inclusion in a risk assessment has been described **[D2:1, 4.2.1]** - the screening may also involve or necessitate selected information on ecosystem transfer, likely exposure, and effects **[D4]**; **[FRED]**; **[D5]**.

Decision-making and different routes for the source characterization are schematically illustrated in Figure 2-2.

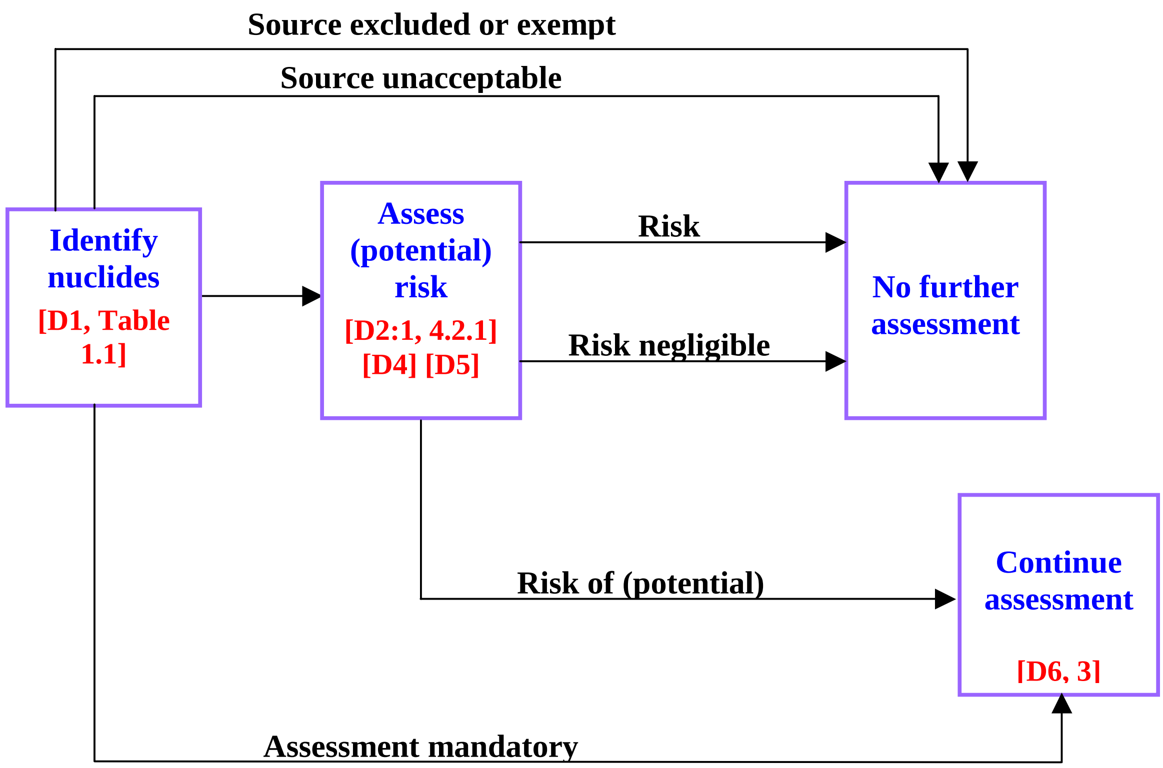

Figure 2-2 Schematic representation of source characterisation, involving - as appropriate - an initial screening, and position of supporting documentation within the Framework.

2.2.1 Selection of radionuclides for consideration within the Framework

A sub-set of radionuclides from 20 elements was selected for consideration within the development of the Framework (Table 2-1). Full source characterization and hazard identification, as indicated above, were not performed during the selection of radionuclides. The selection criteria were as follows:

- radionuclides routinely considered in both regulatory assessments of waste disposal and releases from different facility types, and emergency planning for accidental releases;

- a range of environmental mobilities and biological uptake rates;
- both anthropogenic and natural radionuclides;
- representatives of α, β and γ emitters; and,
- data availability.

This list has been used mainly to define limits for the work within the FASSET project. It should also be noted that for many of these radionuclides, considerable deficiencies exist for later phases of the assessment, *e.g.* transfer and effects.

2.2.2 Screening method for identification of contaminants of potential concern

Hazard identification starts with a broad approach, considering various radionuclides, their environmental fates and effects. A flow chart for the screening of radionuclides and a description of criteria useful in the screening process are described in **[D2:1, 4.2.1]**. The criteria suggested for use in screening of radionuclides are summarised below.

2.2.3 Further criteria for initial screening

As indicated above and in Figure 2-2, additional judgment may require consideration of exposure and effects data already in the initial source characterization. Possibly, this can involve additional screening tools such as the **[FRED]**. Should this not be possible, the assessor has no choice other than to perform a complete assessment, although the level of detail may differ depending on circumstances and on expert judgment.

Furthermore, due consideration needs also to be taken on the temporal as well as spatial scales; for example, a time-limited discharge affecting a minor area that is subject to institutional control normally causes less concern than a long-term release with global dispersion.

2.3 Observations and recommendations

At the present, the Framework contains general advice as to the initial source characterization and decisions based on this characterization. For a number of radionuclides, transfer and effects data are lacking for later stages in the assessment. However, the Framework is probably in most cases robust enough to be applicable to other radionuclides, providing that input data are known.

The primary objective in building the Framework was to provide ‘realistic’ estimates of environmental impact for information purposes, which *inter alia* necessitates an integral effects analysis. Since the approach was not designed for compliance purposes, the Framework does not provide guidance on screening levels for, *e.g.*, radionuclide concentrations in different environmental media. However, the methodology developed within FASSET would facilitate derivation of such screening levels, following the adoption of appropriate criteria for screening.

Table 2-1 Radionuclides selected for consideration within the Framework.

Radionuclide (Element Group)	Principal Radioisotopes ($T_{½}$)	Radiation type	Sources
H (Ia)	^{3}H (12 y)	β^-	Cosmic, Fission, activation
C (IVb)	^{14}C (5600 y)	β^-	Cosmic, activation
K (Ia)	^{40}K (1.3×10^{9} y)	β^-, γ	Primordial
Cl (VIIb, halogen)	^{36}Cl (3.01×10^{5} y)	ε, e^-	Neutron activation
Ni (VIII, heavy metal)	^{63}Ni (96 y) ^{59}Ni (7.5×10^{4} y)	β^- β^+, ε	Neutron activation
Sr (IIa)	^{89}Sr (50.5 d) ^{90}Sr (28.5 y)	β^-, γ	Fission
Nb (Va)	^{94}Nb (2.03×10^{4} y)	β^-, γ, e^-	
Tc (VIIa,)	^{99}Tc (2.13×10^{5} y)	β^-, γ, e^-	Fission
Ru (Group VIII, heavy metal)	^{106}Ru (368 d)	β^-	Fission
I (VIIb, halogen)	^{129}I (1.57×10^{7} y) ^{131}I (8.04 d)	β^-, γ, e^- β^-, γ	Fission
Cs (Ia)	^{134}Cs (2.06 y) ^{137}Cs (30 y) ^{135}Cs (2.0×10^{5} y)	β^-, β^+, γ β^- β^-	Fission
Po (VIb,)	^{210}Po (138 d)	α, γ	^{238}U decay series
Pb (IVb, heavy metal)	^{210}Pb (22 y)	β^-, γ	^{238}U decay series
Ra (IIa)	^{226}Ra (1600 y)	α, γ	^{238}U decay series
Th (Actinide series)	^{227}Th (18.7 d) ^{228}Th (1.9 y) ^{230}Th (7.7×10^{4} y) ^{231}Th (25.5 h) ^{232}Th (1.4×10^{10} y) ^{234}Th (24.1 d)	α, γ, e^- α, γ α, γ, e^- β^-, γ, e^- α, γ β^-, γ, e^-	Natural, U & Th series decay chains
U (Actinide series)	^{234}U (2.45×10^{5} y) ^{235}U (7.04×10^{8} y) ^{238}U (4.47×10^{9} y)	α, γ α α, e^-	Natural
Pu (Actinide series)	^{238}Pu (88 y) ^{239}Pu (2.4×10^{5} y) ^{240}Pu (6.5×10^{3} y) ^{241}Pu (14.4 y)	α, β^-, γ α, γ α, e^- α, β^-, γ	Activation-Neutron capture
Am (Actinide series)	^{241}Am (432 y)	α, γ	Activation-Neutron capture decay of ^{241}Pu
Np (Actinide series)	^{237}Np (2.1×10^{6} y)	α, γ, e^-	Activation-Neutron capture
Cm (Actinide series)	^{242}Cm (163 d) ^{243}Cm (28.5 y) ^{244}Cm (18.1 y)	α, γ α, γ, ε, e^- α, γ	Activation-Neutron capture

Screening levels (or guidance values) and methods for how to apply them in assessments, including supporting software, have been developed by, *e.g.*, the US Department of Energy [Higley *et al*., 2001]. These guidance values have been derived on the basis of interpreting 'no-effect-dose-rates' from IAEA [IAEA, 1992] as being 'environmentally safe'. It can be noted, however, that the IAEA values were never intended to be developed into standards. Similarly, the FASSET effects overview **[D4]**, although stating that there are few indications of environmentally significant effects at dose rates below 100 μGy h^{-1}, points to fundamental data gaps that advise against using such values as being universally safe. In a more precautionary approach, the Environment Agency in the UK [EA, 2002] has advised using environmental concentrations derived on the basis of 5% of the IAEA dose rates as an initial screening level.

It appears that a more systematic approach to development of screening criteria is required, taking into account existing knowledge and data gaps, and exploring experimentally and through expert elicitation procedures to extrapolate existing knowledge to other nuclides, organisms, effects, etc. Part of the EC 6th Framework Programme project ERICA is devoted to this issue.

Table 2-2 Selection/screening criteria for initial source characterisation

Type of criterion	Criterion
Source term	Total release of radioactivity and relative contribution of each isotope
	Distribution of release over time
	Changes with time in the relative contribution of each isotope
	Origin of radionuclides; the way in which radionuclides reach the receptor ecosystem, *e.g.* from below ground, as release directly to surface water, deposition to land or water surfaces
	Chemical speciation of the released radionuclides
Physical parameters	Half-lives (relevant to the time scale of interest)
	Type and energy of radiation (relevant to the exposure pathways of interest; internal contamination is of most relevance for α- and β-emitters whereas external contamination is most relevant in the case of β- and γ-emitters.
Environmental fate	Solubility of the element
	Reactivity of the element with the solid phase (sorption behaviour)
	Isotopic dilution of radionuclides in the receptor systems
Biological activity	Degree of hydrolysis
	Reaction with biological ligands
Potential chemical toxicity	Allocated to two classes:
	Trace elements with a stable element or a competitor (biochemically analogous element), which are macro- or micro-nutrients.
	Elements with no stable competitor, no known biological function

3 Ecosystems and selection of reference organisms

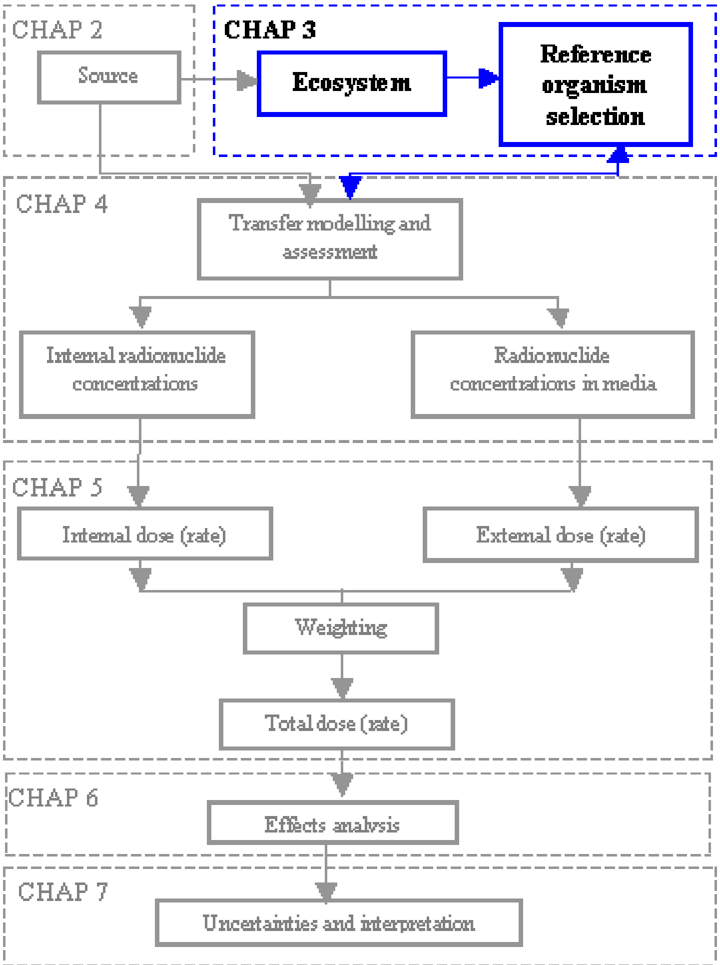

Figure 2-1 Position of the ecosystem characterisation and selection of reference organisms within the Framework.

3.1 Introduction

The identification and subsequent characterization of the ecosystem(s) receiving and affected by the radionuclide input constitute the second essential input into the assessment flow-chart (Figure 3-1). Collation of underlying information about the ecosystem(s) to be considered is important at this stage as this forms the basis of the analysis of exposure pathways and choice of exposure models to be used or developed, as well as the selection of organisms to be considered in the assessment.

A particular problem arises from the necessity to provide some generalisation, without losing precision in the assessments. While ecosystems can be given fairly limited spatial boundaries usually the available data to be assembled within the assessment framework are general and do not support more than generalised descriptions of ecosystems.

Furthermore, 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 'representative' targets, where – again - 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 beyond credibility. The Framework deals with this problem through applying the concept of 'reference organisms', proposed initially by Pentreath and colleagues (*e.g.* Pentreath and Woodhead, 2001). 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".

The reference organisms are thought of as a suite which, taken together, are likely to cover the range of both radiation exposures and radiosensitivities which may arise within contaminated ecosystems.

3.2 Overview of Framework information and tools

Europe includes a range of ecosystems from the Mediterranean systems in the south to the Polar regions in the north. European ecosystems were preselected in order to define the European ecosystems for which generalised data and models were available or could be developed within the duration of the project. Within the FASSET project, thus, seven types of ecosystem are considered (Table 3-1). For each type of ecosystem,

- a data collation was carried out, which was presented as an overview of the ecological characteristics of the ecosystem type in Europe; and,
- radiation exposure pathways were evaluated in order to subsequently allow for identification of maximally exposed ecosystem components.

Table 3-1 European ecosystems considered within the Framework, and source of detailed information.

Ecosystem	Data collation
Terrestrial ecosystems	
Forests	[D1: App.1, 2]
Semi-natural pastures and heath lands	[D1: App.1, 3]
Agricultural ecosystems	[D1: App.1, 4]
Wetlands	[D1: App.1, 5]
Aquatic ecosystems	
Freshwater ecosystems	[D1: App.2, 2]
Marine ecosystems	[D1: App.2, 3]
Brackish water ecosystems	[D1, App.2, 4]

The choice of reference organisms was based on their radioecological sensitivity, *i.e.* the potential of the organism, through feeding habits and habitat occupancy, to be exposed to significant dose rates from radionuclides in their environment. The modelling studies and expert judgement upon which the selection of reference organisms has been based are described in **[D1:1]** for terrestrial ecosystems and **[D1:2]** for aquatic ecosystems. The relevant sections of **[D1]** where information about selection of the reference organisms can be found is shown in Table 3-2 below.

Table 3-2 Information concerning the choice of reference organisms

Information relevant to choice of reference organisms		Relevant section of [D1]
Assessment of radioecological sensitivity	External exposure	[D1, 2.2.1]
	Internal exposure	[D1, 2.2.2]
Terrestrial ecosystems; selection of reference organisms	Soil	[D1, 3.1.1]
	Herbaceous layer	[D1, 3.1.2]
	Canopy	[D1, 3.1.3]
Aquatic ecosystems; selection of reference organisms	Bed sediment	[D1, 3.2.1]
	Water column	[D1, 3.2.2]

The organisation of the ecosystem analysis using the supporting documentation is schematically shown in Figure 3-1.

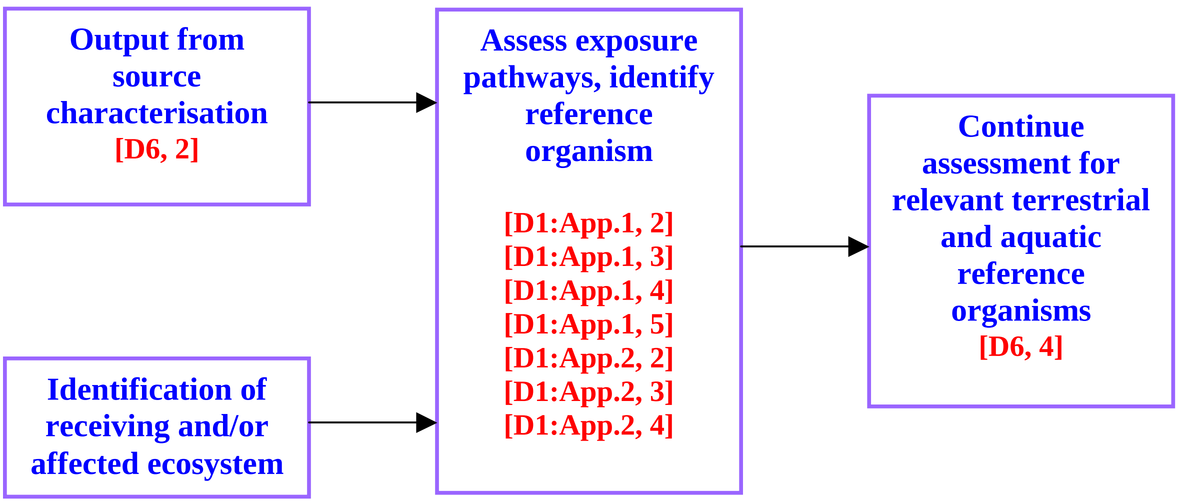

Figure 3-2 Organisation of ecosystem analysis and reference organisms selection, and supporting Framework documentation.

3.2.1 Brief overview of considered ecosystems

- *Forests*. Communities dominated by trees; the Food and Agriculture Organization of the United Nations defines forest as land with tree crown cover of more than 10 %, an area of more than 0.5 ha and with trees which are able to reach a minimum in situ height of 5 m at maturity.

- *Semi-natural pastures and heathlands.* A broad range of ecosystems including mountain (*e.g.* Alpine pastures) and upland grasslands (*e.g.* those characteristic of many upland areas of the UK), heath and shrub lands (*e.g.* Mediterranean Garrigue), saltmarshes and some Arctic ecosystems. These ecosystems are termed 'semi-natural' since, whilst they comprise natural species not introduced by man, they have been influenced by human use, for instance by the grazing of livestock.
- *Agricultural ecosystems*. Includes arable land, intensively managed pastures and areas used for fruit production. For the purposes of this assessment wildlife have not been considered as part of the agricultural ecosystem.
- *Wetlands*. Areas of marsh, fen, peatland, *etc*., whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish, or salt.
- *Freshwaters*. All freshwater systems including rivers and lakes.
- *Marine*. In terms of sea areas, FASSET defines the European marine ecosystem as the North-Eastern section of the Atlantic Ocean and its marginal seas including the Mediterranean Sea, Greenland Sea, the Irish Sea, North Sea, Norwegian Sea, Skagerrak, Kattegat and Barents Sea.
- *Brackish waters*. Within the scope of the project only the non-tidal, shallow Baltic Sea; organisms are immigrants from either marine or freshwater systems.

3.2.2 Selection of compartments to simplify assessments

Based upon knowledge of the distribution of radionuclides within the environment a simplified compartmentalisation of the ecosystems has been used:

- Aquatic ecosystems have been considered as two compartments; bed sediment and the water column. Organisms which spend all or most of their time in the water column will generally receive much lower external radiation doses than will the benthic (bottom dwelling) organisms, because the water provides effective shielding from radiation emitted by radionuclides accumulated in sediments. However if these organisms exhibit bioconcentration[2] of radionuclides to a high degree they merit consideration as candidates for further exposure and effects assessments.
- Terrestrial ecosystems have been considered as the soil, herbaceous layer and canopy compartments. Some organisms may be represented in different compartments, most notably the roots and above ground parts of plants. The term 'herbaceous layer' is used here to represent the understorey layer of forests, crop or pasture layer of agricultural systems, and the above ground components of semi-natural heathlands and pastures, and wetlands.

[2] Here, *bioconcentration* is used to refer to a situation where an organism accumulates internally (inside the organism body) a radionuclide to concentrations higher than those that exist in the surrounding media, *e.g.* water column (dissolved phase), sediment or soil.

3.2.3 Selection of reference organisms for the purpose of the Framework

The reasoning for choosing the reference organisms is described in **[D1]**. In summary, the choice of reference organisms was based on considerations of:

- whether the habitat or feeding habits of the organism are likely to maximise its potential exposure to radionuclides, based on an understanding of the distribution of the different radionuclides within the ecosystem;
- whether the organism exhibits radionuclide-specific bioconcentration which is likely to maximise internal radionuclide exposures in particular circumstances – this was addressed through taking into account the environmental behaviour of the radionuclides;;
- whether the position of the organism within the foodchain (*e.g.* top predator) is such that biomagnification[3] of radionuclides up the foodchain may lead to enhanced accumulation; and,
- the simplified compartmentalization of the ecosystems which has been used **[3.2.2]**.

In the selection of reference organisms, aspects of comparative radiosensitivity and ecological function have been taken into account. Different radiosensitivities at different stages of the life-cycle have been considered. In addition, particularly radiosensitive organisms have been considered even when they are not radioecologically sensitive.

Based on these considerations, *ca* 30 reference organisms were identified as representatives of the seven ecosystems and the five environmental compartments selected on the basis of the ecosystems overview. Note that the reference organisms are not ‘organisms’ or ‘species’ as such, they rather represent biological components of importance for functioning and integrity of the ecosystems. The list of reference organisms is presented in Tables 3-3 and 3-4.

The assessment has covered the full range of trophic levels and functions within ecosystems. There are broad similarities in the foodwebs of the ecosystems considered. Therefore, the similar basic foodweb structures could be considered irrespective of ecosystem. The trophic levels and the organisms considered within those trophic levels are outlined in table 3-5.

3.3 Observations and recommendations

Whilst the set of organisms identified in Tables 3-3 and 3-4 form a basis for the assessment, it needs to be borne in mind that variations within these organisms may be substantial; this relates to ecological information of the type presented in **[D1:App.1]** and **[D1:App2],** as well as dimensions which affect modelling approaches **[D3]** and **[D5]**, and life history **[D5]**, which will be further considered in subsequent sections of this Framework. The use of the reference organisms for the specific assessment purpose must, therefore, be back-checked against supplementary information, in order to ascertain the appropriateness of the reference organism and to estimate associated uncertainties.

[3] *Biomagnification* is used to refer to a situation where concentrations of radionuclides in organisms increase as one moves higher up the foodchain.

A number of groups of ‘candidate’organisms were initially selected as potential reference organisms on the basis of their radioecological characteristics, but were not included in the final list because of the limited data available for such species. These organisms were:

- Reptiles; may be exposed to external radiation because of contact with the ground and long biological half-lives for some radionuclides. However, reptiles were excluded on the basis of primarily data shortage.
- Reptile eggs may also be exposed to external radiation as they often are buried. There is however, lack of knowledge on exposure of and transfer to reptile eggs.
- Fish eggs (in sediments). Fish eggs laid on bed sediments will be exposed to external beta gamma radiation from the sediments. Depending on the size of the eggs, alpha radiation from the sediments may also penetrate far enough into the egg to deliver a significant dose. Such eggs merit consideration as a reference dose organism; however, unless radionuclides are concentrated within the eggs to a greater extent than they are in the sediment itself, the doses calculated for bacteria will represent a limiting case for such fish eggs.
- Fish eating birds (e.g. cormorant, heron) are ‘top predators’. However explicit consideration of fish eating birds would only be necessary if they showed significantly higher bioconcentration than do aquatic mammals; currently we have no evidence of this.

The examples of rejection (above) as well as the arguments for inclusion (Tables 3-3 and 3-4), may guide users of the Framework to informed decisions on the selection of reference organisms, and also together with the supplementary information provide assistance to the estimation of uncertainties associated with the application of the reference organism concept.

Table 3-3 Reference organisms for the terrestrial ecosystems considered.

Environmental compartment	Organism	Forest	Semi-natural	Agricultural	Wetlands	Rationale
Soil	Micro-organisms	Yes	Yes	No	Yes	Maximum external exposure to radionuclides in soil including alpha emitters, because of their small size.
	Worm	Yes	Yes	No	Yes	High external exposure to beta and gamma emitting nuclides in soil *plus* potential to bioconcentrate internal emitters.
	Plants	Yes	Yes	Yes	Yes	Plant roots (mycorrhizae) receive a high external exposure to beta and gamma emitting nuclides in soil *plus* are the plant component with highest concentrations of many radionuclides.
	Fungi	Yes	Yes	No	No	Fungal hyphae receive a high external exposure to beta and gamma emitting nuclides in soil *plus* have a potential high bioconcentration of some radionuclides.
	Burrowing mammal	Yes	Yes	No	No	High external exposure to beta and gamma emitting nuclides in soil *plus* potential to ingest soil associated with invertebrate prey or whilst grooming etc; may be more exposed to ^{226}Ra than other mammals. Radiosensitive.
Herbaceous layer	Bryophytes	Yes	Yes	No	Yes	Well documented as bioconcentrator of many aerially deposited radionuclides. In many environments, most contaminated primary producer.
	Grass, herbs and crop plants	Yes	Yes	Yes	Yes	The foliage can intercept aerially deposited radionuclides, which may lead to high acute exposure. Mobile radionuclides may bioconcentrate in some plant species.
	Shrubs	No	Yes	Yes	No	As above, some species have considerably higher uptake of some radionuclides than other plant types.
	Detritivorous invertebrate	Yes	Yes	No	No	High concentrations of a number of radionuclides. Comparatively highly exposed to external radiation as live in litter layer.

Environmental compartment	Organism	Forest	Semi-natural	Agricultural	Wetlands	Rationale
	Herbivorous mammal	Yes	Yes	Yes	Yes	Comparatively high transfer of mobile radionuclides (Cs, I, Sr) and accumulate less mobile radionuclides (Pu, Am, Ru,) in tissues such as liver. Radiosensitive.
	Carnivorous mammal	Yes	Yes	No	Yes	Top predator may biomagnify some radionuclides (observed for Cs). Radiosensitive.
	Bird egg	Yes	Yes	No	No	The bird egg can potentially be highly exposed to external radiation; accumulation of Sr in shell and comparatively high transfer of some radionuclides to egg contents. Likely to be more radiosensitive life-stage.
Canopy	Trees	Yes	No	Yes	No	The tree foliage has the ability to intercept large proportion (up to 90 %) of aerially deposited radionuclides.
	Invertebrate	Yes	No	No	No	Residing in the canopy of trees will lead to exposure as a consequence of the ability of the canopy to intercept aerially deposited radionuclides.

Table 3-4 Reference organisms for the aquatic ecosystems considered.

Environmental compartment	Organism type	Marine	Brackish	Freshwater	Rationale
Sediment	Bacteria	Yes	Yes	Yes	Maximum external exposure to particle reactive nuclides in sediment *including alpha emitters*
	Worm	Yes	No	No	High external exposure to beta gamma emitting nuclides in sediment *plus* potential to bioconcentrate internal emitters. Consideration of insect larvae for brackish and freshwater would better fill this niche for those systems.
	Insect larvae	No	Yes	Yes	High external exposure to beta gamma emitting nuclides in sediment *plus* potential to bioconcentrate internal emitters. Important component of freshwater benthic biomass.
	Bivalve mollusc Gastropod mollusc	Yes	Yes	Yes	High external exposure to beta gamma emitting nuclides in sediment *plus* proven high accumulation of particle reactive radionuclides *e.g.* ^{106}Ru, ^{210}Po, ^{239}Pu, ^{241}Am. Rationale for separate inclusion of bivalves and gastropods requires review – are CFs significantly different?
	Crustacean (lobster, crayfish)	Yes	Yes	Yes	High external exposure to beta gamma emitting nuclides in sediment; potential for bioconcentration of particle reactive radionuclides; evidence of high nuclide specific bioconcentration (*e.g.* ^{99}Tc, ^{210}Po)
	Amphibian	No	No	Yes	High exposure to external radiation from beta gamma emitters in sediments – there is little or no data on bioaccumulation.
	Fish (*e.g.* plaice, sole, catfish)	Yes	Yes	Yes	High external exposure to beta gamma emitting nuclides in sediment coupled with bioaccumulation of conservative radionuclides (e.g ^{137}Cs). Fish eggs might be considered, but unless there are data showing high bioconcentration, doses for bacteria will be a 'worst case'.

Environmental compartment	Organism type	Marine	Brackish	Freshwater	Rationale
	Fish eggs	Yes	Yes	Yes	Fish eggs laid on bed sediments will be exposed to external beta gamma radiation from the sediments. Depending on the size of the eggs, alpha radiation from the sediments may also penetrate far enough into the egg to deliver a significant dose. However, unless radionuclides are concentrated within the eggs to a greater extent than they are in the sediment itself, the doses calculated for bacteria will represent a limiting case for such fish eggs.
	Vascular plant	No	Yes	Yes	High exposure of roots to external radiation from beta gamma emitters in sediments. Proven ability to selectively bioaccumulate (*e.g.* ^{226}Ra, ^{238}U)
	Mammals (*e.g.* seals, whales, otters)	Yes	Yes	Yes	Position at top of aquatic foodchain may predispose to bioaccumualtion and/or biomagnification. Perceived high conservation value; likely to be radiosensitive
	Wading birds (*e.g.* tern, mallard)	Yes	Yes	Yes	Wading habit maximises external exposure to beta gamma emitters in sediments; feeding on sediment invertebrates maximises possible internal exposure to particle reactive radionuclides, including alpha emitters. Perceived high conservation value (*e.g.* RAMSAR sites).

Environmental compartment	Organism type	Marine	Brackish	Freshwater	Rationale
Water column	Phytoplankton (microalgae)	Yes	Yes	Yes	Proven high bioconcentration of certain radionuclides (especially particle reactive) *e.g.* ^{210}Po, ^{226}Ra, ^{239}Pu
	Zooplankton	Yes	Yes	Yes	Bioconcentration data limited but shown to be high in some cases (*e.g.* ^{210}Po). Represents juvenile form of many species, may be specially radiosensitive including fish eggs
	Macroalgae (seaweed)	Yes	Yes	No	Proven ability to selectively bioaccumulate (*e.g.* ^{99}Tc, ^{106}Ru)
	Fish (*e.g.* cod, salmonids)	Yes	Yes	Yes	Proven ability to bioaccumulate (*e.g.* ^{137}Cs); predatory feeding habits may lead to biomagnification
	Mammals (*e.g.* seals, whales, otters)	Yes	Yes	Yes	As above; position at top of aquatic foodchain may predispose to bioaccumualtion and/or biomagnification. Perceived high conservation value; likely to be radiosensitive
	Wading birds (*e.g.* tern, mallard)	Yes	Yes	Yes	Wading habit maximises external exposure to beta gamma emitters in sediments; feeding on sediment invertebrates maximises possible internal exposure to particle reactive radionuclides, including alpha emitters. Perceived high conservation value (*e.g.* RAMSAR sites)

Table 3.5 The organisation of reference organisms within different trophic levels.

	Terrestrial	Aquatic	
		Pelagic	Benthic
Primary producers			
	Trees, shrubs, grasses, herbs, bryophytes and microflora	Phytoplankton	Micro- and macroalgae and vascular plants
Primary consumers (Herbivores and omnivores)			
	Microorganisms (protozoa), invertebrates (insects), vertebrates (mammals and birds)	Protozoa and zooplankton	Detritophagues: Deposit feeders (*e.g.* worms, echinoderms, crustaceans) Filter feeders (*e.g.* molluscs)
Predators			
	Vertebrate and invertebrates carnivores	Vertebrates (fishes, reptiles, mammals) and invertebrates (mollusk and crustaceans)	Vertebrates (fishes and mammals).
Higher predators			
		Vertebrates (carnivorous mammals, fish)	Vertebrates (carnivorous mammals, fish)
Decomposers			
	Vertebrates, invertebrates, microorganisms, saprophytic macrofungi		

4 Transfer modelling and assessment

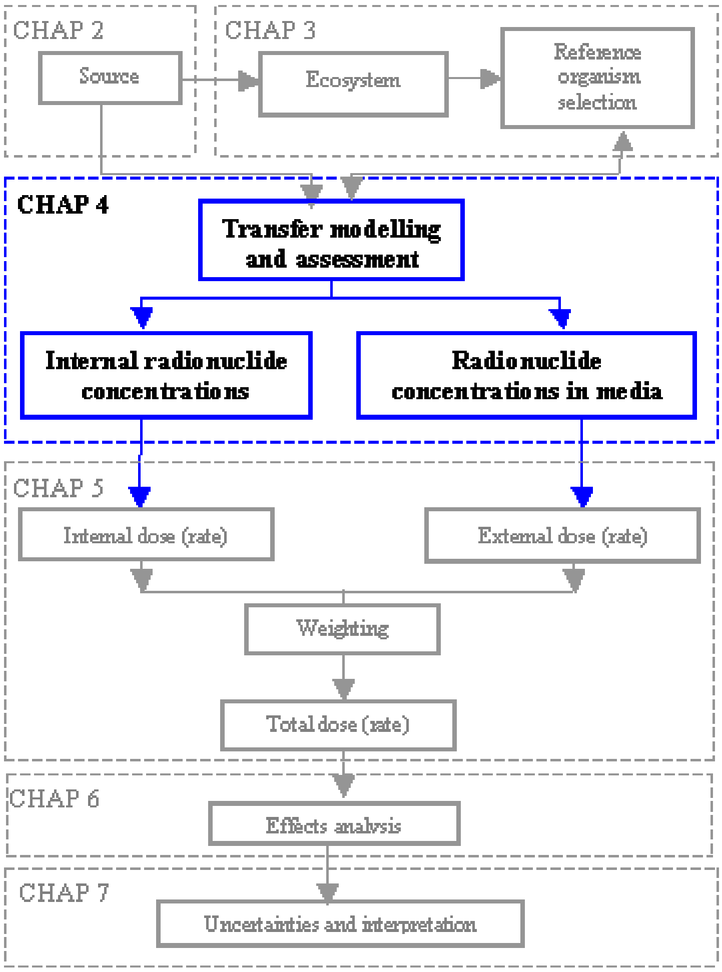

Figure 4-1 Position of the transfer modelling and assessment within the Framework.

4.1 Introduction

The total dose received by an organism is the sum of internal and external doses. Different organisms may be exposed to internal and external doses to differing extents, dependent upon the contamination scenario and the organisms' habits. The two pathways are therefore considered separately.

The external exposure is dependent on how radionuclides are distributed within the ecosystem and the habits of the organism. The distribution of radionuclides among different ecosystem components depends on the time that has passed since the system was contaminated and the contamination scenario. Under conditions of chronic contamination within terrestrial ecosystems and in the mid to long-term following acute deposition, the majority of the radionuclide inventory is found within soil. Therefore, organisms living within, or partially within the soil will be the most exposed to external irradiation. In the case of aerial contamination of terrestrial ecosystems, the vegetation cover will intercept a large proportion of deposited radionuclides and the above ground plant parts, and animals inhabiting the vegetative layers will be amongst the most externally exposed organisms. Radionuclides behaviour and distribution within aquatic ecosystems are determined primarily by the partition of radionuclides between the dissolved phase and the suspended sediments in the water column; radionuclides, which become sorbed onto suspended sediments, are subsequently incorporated into bed sediments.

The internal exposure is proportional to the uptake of radionuclides by organisms. This is determined by the availability of the radionuclides for biological uptake (bioavailability[4]) and the capacity of the organisms to concentrate the incorporated radionuclides with respect to the surrounding media (*i.e.* bioconcentration) or the feed (*i.e.* biomagnification).

The identification of actual species facilitates the collection of basic ecological information that is required for an exposure assessment (including both transfer modelling/assessment and dosimetry). A number of species have been identified as being representative of one of the reference organisms and the basic ecological information presented.

4.2 Overview of Framework information and tools

Within the Framework, tools are available to allow activity concentrations in biota and their habitats to be derived from a starting point defined by a release into the environment. The starting points for the exposure assessment are as follows:

Aquatic ecosystems:	Unit activity concentration in water	(Bq l^{-1})
Terrestrial ecosystems:	Unit rate of deposition	(Bq m^{-2} y^{-1})
	Unit activity in air (^{3}H and ^{14}C only)	(Bq m^{-3})
	Unit activity concentration in soil	(Bq kg^{-1}dry mass)

From these starting points, the Framework provides tools for the assessment of radionuclide transfers within selected ecosystems in order to allow the concentrations of radionuclides in the physical compartments of the environment and in the biota to be predicted. These concentrations are required in order to calculate the external and internal dose rates.

Physical transport models simulating the initial transport of contaminants from the point of release to the point of entry into the selected ecosystems are not incorporated within the Framework. Previously developed models of physical transport were generally available to potential users of the Framework to provide the required starting point radionuclide concentrations/deposition rates. However, a review of models applicable to the aquatic environment was conducted as an aid to choosing methods to derive the concentration of radionuclides in water **[D5: App2, 6],** including an approach to predict their concentrations in water, suspended sediment and deposition to sediment from the discharge rate into a river (**[D5:App 2, 9]**) .

4.2.1 Sediment - water distribution for aquatic ecosystems

Sediment–water distribution coefficients (k_d-values) for freshwater (**[D5, table 4-5]**) and marine (**[D5, table 4-7]**) ecosystems have been compiled from the literature in order to

[4] *Bioavailability* is defined here as the potential of the radionuclides in a certain media for biological uptake.

allow the prediction of the concentration in sediment from the concentration in water (assuming equilibrium between the two phases).

4.2.2 Transfer to organisms

Transfer parameters enabling the activity concentration in reference organisms to be predicted from concentrations in environmental media or deposition rates, as appropriate, are provided as a series of look-up tables. There is a look-up table for each radionuclide and for each ecosystem, see Table 4-1, where available transfer parameters are given for reference organisms identified for each ecosystem. In addition to equilibrium transfer parameters (ratio of activity concentration in reference organism to activity in appropriate media), in semi-natural pasture/heathland and agricultural ecosystems, transfer values for chronic deposition relating the activity concentration in a reference organism to the deposition rate after 50 years deposition are also given. Look-up tables present best estimate values with an indication of confidence level. For some ecosystems basic statistical information on the data are available **[D5: App 2]**.

The transfer parameters have been derived using a number of approaches, including reviews of published literature, analyses of monitoring data and the application/adaptation of appropriate food chain transfer models. The completeness of the look-up tables and the methods used to derive transfer values varied between the different ecosystem types, depending upon the availability of existing models and data (Table 4-2).

In the case of marine ecosystems, many of the required transfer parameters were available from IAEA reviews, although the IAEA publications focused on species and organs important in the human foodchain. Allometric (body mass dependent) models were used to derive transfer parameters for sea birds and sea mammals for some radionuclides.

For freshwater ecosystems, a database was compiled. However, data were only available to provide values in the look-up tables for 20 % of the radionuclide-reference organism combinations required within the Framework. For brackish waters few observed data were available and these were restricted to predominantly Cs with limited observations for Pu and Sr. A carbon dynamics model was used to derive look-up table values for ^{14}C in brackish water ecosystems.

For semi-natural pasture/heathland ecosystems, an empirical database was complied from a literature review and previously unpublished sources (largely data supplied from the former Soviet Union). The majority of these data was for Cs, Sr and natural radionuclides (e.g. U). To fill-in for missing data, existing human foodchain models were adapted and combined with allometric relationships to predict transfer parameters for mammalian reference organisms. The same model was used to generate look-up tables for chronic deposition in semi-natural pastures/heathlands. Specific activity approaches were used to generate look-up tables for ^{14}C and ^{3}H. Look-up tables for agricultural ecosystems were derived using established human foodchain models. Empirical data were used to derive look-up tables for Sr and Cs in forest ecosystems and existing forest models were combined with allometric relationships to provide transfer parameters for Pu and Tc.

Comprehensive data for the transfer of radionuclides in wetlands are not available. Therefore, it is recommended that the most appropriate values from look-up tables for either semi-natural or freshwater ecosystems be used.

The approaches used for the derivation of transfer factors for each ecosystem are described in detail in **[D5]**, see Table 4-2.

Table 4-1 Information on transfer factors for organisms in the seven ecosystems considered within the Framework.

Ecosystem	Transfer factor	Appropriate section of D5
Forest	Bq/kg per Bq/m^2	[D5:App1, 1.1]
Semi-natural pasture and heathland	Bq/kg per Bq m^{-2} y^{-1} Bq/kg organisms per Bq/kg soil	[D5:App1, 1.2]
Agricultural	Bq/kg per Bq m^{-2} y^{-1} Bq/kg organisms per Bq/kg soil	[D5:App1, 1.3]
Freshwater	Bq/kg fresh weight per Bq/l	[D5:App1, 1.4]
Marine	Bq/kg fresh weight per Bq/l	[D5:App1, 1.5]
Brackish water	Bq/kg fresh weight per Bq/l	[D5:App1, 1.6]

Table 4-2 Information on modelling.

Ecosystem	Approaches used	Appropriate section of D5
Forest	Dynamic modelling, Kinetic-allometric modelling	[D5:App.2, 2] [D5:App.2, 2]
Semi-natural	Literature review and data collation Specific activity modelling (C-14) Specific activity/allometric model (H-3) Dynamic modelling	[D5:App.2, 3] [D5:App.2, 4.2] [D5:App.2, 4.1] [D5.App.2, 5]
Agricultural	Equilibrium compartmental modelling	[D5, 4.1.4]
Freshwater	Literature review	[D5, 4.1.6]
Marine	Literature review and data collation Kinetic-allometric modelling	[D5:App.2, 7] [D5:App.2, 8]
Brackish	Literature review Ecosystem modelling	[D5, 4.1.8] [D5, 4.1.8.1]

4.2.3 Life history data

The generic reference organism list has been used as a basis for developing tools for the assessment of the exposure of biota. The identification of actual species (or in some cases, families or classes of organisms), representing each of the broadly defined groups, has been helpful both for data collection and for the definition of geometries for dosimetry modelling. In the assessment process it is thus recommended that an appropriate list of "representative" reference organisms is specified and that basic ecological information is collated for each of these flora and fauna. The information required in an assessment relates to the subsequent assessment of exposure. Life history data for the organisms, identified as representative of the reference organisms, have been presented in the D5 sections, shown in Table 4-3. The type of information collated for each specific example of reference organisms is reviewed in Table 4-4.

Table 4-3 Representative organisms and where their life history data can be found.

Ecosystem	Representative species	Appropriate section of D5
Forest and semi-natural	Creeping bent, Heather, Reindeer lichen, Cep, Scots pine, Common oak, Earthworm, Woodlouse, Wood ant, Red grouse (egg), Mole, Rabbit, Weasel, Red fox, Moose.	[D5:App.2, 1.1]
Agricultural	Potato, Carrot, Onion, Lettuce, Tomato, Wheat, Grapevine, Orange, Apple, Olive, Cow, Sheep, Pig.	[D5, 4.1.4]
Wetlands	Select from freshwater and semi-natural species as appropriate	[D5:App.2, 1.1 and 1.2]
Freshwater	Water millfoil, Freshwater clam, Gastropod, Freshwater isopod, Burbot, Perch, Common frog, Muskrat, Common gull.	[D5:App.2, 1.2]
Marine	Phytoplankton, Bladder wrack, Northern shrimp, Blow lug, Blue mussel, European lobster, Plaice, Mackerel, Eider duck[5], Harp Seal	[D5:App.2, 1.3]
Brackish	Select from freshwater and marine as appropriate	[D5:App.2, 1.2 and 1.3]
Rivers	Select from freshwater as appropriate	[D5:App.2, 1.2]

4.3 Observations and recommendations

Physical transport models simulating the initial transport of contaminants from the point of release to the point of entry into the selected ecosystems are not incorporated explicitly within the Framework. This decision was taken initially as models of transport within the physical environment would not be different if developed for the purpose of the Framework, than for existing ones.

It should be noted that there are many gaps in the data available to populate the look-up tables. This is not surprising when there are nearly 200 radionuclide-reference organism combinations for semi-natural terrestrial ecosystems alone. The project has used some (novel) approaches to address some of these data requirements, but it is still not possible to provide complete look-up tables for many radionuclide– reference organism combinations. Whilst approaches to addressing the problem of missing data in the future have been suggested [*e.g.* Beresford *et al.*, in press], some recommendations for users of the Framework on how to cope with the current lack of required transfer parameters are required.

[5] Eider duck (*Somateria mollissima*). This bird is not a wader but the choice of a duck as a representative biota was considered appropriate for numerous reasons, not least the fact that it is in line with approaches that have been taken elsewhere (*e.g.* Copplestone *et al.*, 2001).

Table 4-4 Ecological information for specific examples of reference organisms[6].

Information	Comment
(i) Latin and common English name of the selected species.	Simple assessment
(ii) Biota dimensions (mass, dimensions)	Simple assessment Dimension – represent as ellipsoid and defined length, width depth Required for geometry configuration
(iii) Habitat – configuration and occupancy factors	Simple assessment Required for target source configuration – external dose assessment *E.g.* marine – pelagic, benthic; terrestrial – at soil surface, in soil (depth and orientation), Occupancy factors – fraction of time spent in different habitats – required for average dose rate calculation
(iv) Habitat (dynamic)	*E.g.* does animal hibernate (if so where + time) ? Parts of life-cycle in different habitats – meroplanktonic larvae? Advanced assessment – information required in the calculation of integrated doses
(v) Distribution – Home range.	Advanced assessment – information required in the calculation of integrated doses
(vi) Average life expectancy,	Advanced assessment – information required in the calculation of integrated doses
(vii) Feeding habits	*E.g.* main prey species, Advanced assessment – information required for input to ecological models
(viii) Additional information on lifecycle	*E.g.* viviparous fish, periods spent in freshwater Advanced assessment – information required in the calculation of integrated doses; sensitive periods in life-cycle

The Framework has built upon the recommendations of Copplestone *et al.* [2003] when conducting assessments for which the required transfer parameters are not available.

- The assessment should clearly state that data are not available.
- If data for a specific ecosystem are unavailable consider the suitability of data from other ecosystem types. For instance, transfer values for animals from the semi-natural pastures/heathlands look-up tables could be applied to animals in forest. Similarly, given the absence of data for wetlands appropriate data for freshwater environments or semi-natural pastures/heathlands could be used.
- A transfer (fresh weight activity concentration in organism:fresh weight activity concentration in soil) value of 1 is recommended as being generally conservative for terrestrial environments. There will be exceptions where this assumption is not conservative (e.g. for radiocaesium), but in these cases data will generally be

[6] Simple assessment–basic information required for the calculation of dose rates. An advanced assessment is possibly beyond the scope of the Framework. However, such information may prove useful in the parameterisation of food chain and exposure models.

available for some organism groups for these radionuclides, on which expert judgement can be made.

- For aquatic systems, the highest available concentration factor for a specified radionuclide considering all reference organism types should be compared with the k_d for that radionuclide. The larger number can be selected for the assessment.
- Consider if transfer can be justifiably ignored. For some organisms exposed to beta/gamma emitters the total dose is likely to be dominated by external radiation (e.g. a worm inhabiting soil contaminated by gamma-emitters).
- For some radionuclides, transfer values for radionuclides with a similar biogeochemical behaviour could be employed. For instance, transfer values for Pu could be used to estimate Am activity concentrations.

An assumption of equilibrium between the activity concentration in the reference organisms and the relevant medium is implicit in the values presented in the look-up tables. This may not always lead to a conservative assessment of the internal dose. For instance, in conditions of chronic deposition, the contribution of intercepted deposit to the ingestion of radionuclides by herbivores may be considerably greater than the contribution of root uptake. Similarly the application of concentration ratios to pulse releases to aquatic ecosystems has restricted usefulness. Limitations on the use of concentration ratios and assumed equilibrium are more fully discussed in **[D5, 3.2.2]** and dynamic modelling approaches to address these problems are presented in **[D5: App.2]**. A more detailed introduction to the information contained in the Appendix tables is given in **[D5, 4]**.

5 Dosimetry

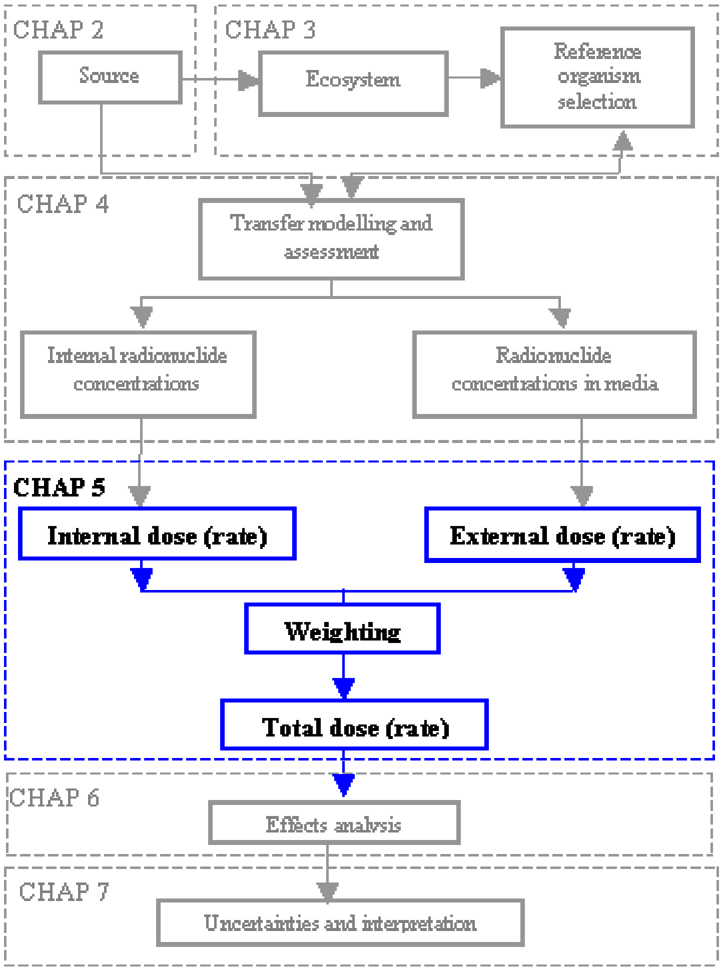

Figure 5-1 Position of dosimetry within the Framework.

5.1 Introduction

Information on internal and external radionuclide concentrations are used for calculation of dose (rates), which – after incorporation of an appropriate weighting factor (if any) – form the basis for a subsequent dose-effect and dose-response analysis.

The Framework uses the absorbed dose as the basic quantity for assessing exposures to ionising radiation. Absorbed dose is defined as the amount of energy that is absorbed by a unit mass of an organ or organism; it is given in units of gray (Gy). The generic reference organism list has been used as a basis for selecting suitable target geometries/phantoms for dosimetric modelling. The dosimetry, as developed and applied for the purpose of the Framework, is described in **[D3]**. Look-up tables have also been compiled in the Handbook, **[D5:App.1, 2]**.

5.2 Overview of Framework information and tools

Dosimetric models have been developed for the estimation of dose from individual radionuclides, including naturally occurring radionuclides. The models are described and used to calculate radionuclide-specific dose conversion coefficients, DCCs, which have been presented as look-up tables, referred to in Table 5-1.

Table 5-1 Tables containing radionuclide specific dose conversion coefficients (DCCs).

Ecosystem/organism type	External/Internal Irradiation	Other details about DCC calculations	Relevant part of Deliverable 3
Organisms living on the soil	External	Planar source at soil surface	[D3, Table 3-8]
Organisms living on the soil	External	10cm thick contaminated soil layer	[D3, Table 3-9]
Organisms living in the soil	External	50 cm thick soil layer	[D3, Table 3-10]
Meristems of terrestrial plants	External	Planar source at soil surface	[D3, Table 3-11]
Terrestrial animals	Internal	Unweighted for RBE	[D3, Table 3-12]
Terrestrial animals	Internal	Weighted for RBE	[D3, Table 3-13]
Coastal-estuarine	Internal		[D3, Table 4-5]
Coastal-estuarine	External		[D3, Table 4-6]
Freshwater-estuarine	Internal		[D3, Table 4-7]
Freshwater-estuarine	External		[D3, Table 4-8]

The organism geometries, which were chosen to be consistent with the reference organisms and ecosystems adopted within FASSET have been tabulated in documentation overviewed in Table 5-2.

Table 5-2 Information relevant to definition of geometries for Framework reference organisms.

Selected geometries of reference organisms	Relevant part of Deliverable 3
Marine	[D3, Table 2-3 and 4-1]
Freshwater	[D3, Table 2-4 and 4-1]
Brackish	[D3, Table 2-5]
Terrestrial	[D3, Table 2-6]

Background dose rates have been calculated for both terrestrial and aquatic environments. Special emphasis is given to the radionuclides ^{238}U, ^{232}Th, ^{230}Th, ^{228}Ra, ^{226}Ra, ^{222}Rn, ^{210}Po and ^{40}K. These data are used to estimate natural background exposures to biota. The details of the calculations and results can be found in the sections listed in Table 5-3.

Table 5-3 Information relevant to background activity and dose rates.

Background data	Relevant part of Deliverable 3
Background radioactivity levels	
Rocks and soil (global)	[D3, Table 5-1]
Soil (European)	[D3, Table 5-2]
Terrestrial organisms	[D3, Table 5-4]
Seawater	[D3, Table 6-1]
Marine sediment	[D3, Table 6-2]
Marine organisms	[D3, Table 6-3]
Freshwater	[D3, Table 6-6]
Freshwater sediment, distribution factors	[D3, Table 6-7]
Freshwater organisms, concentration factors	[D3, Table 6-8]
Background dose rates	
External exposure, terrestrial	[D3, Table 5-3]
Internal exposure, terrestrial	[D3, Table 5-4]
Marine, unweighted	[D3, Table 6-4]
Marine, weighted	[D3, Table 6-5]
Freshwater, unweighted	[D3, Table 6-9]
Freshwater, weighted	[D3, Table 6-10]

5.2.1 Methods

Definition of geometries.

The list of reference organisms drawn up for each of the environments being considered has been used as a basis for selecting suitable target geometries or "phantoms" for the dose calculations. The dimensions and shape were derived in many cases from the adult form of the biota. The shape of the reference organisms was approximated by spheres, cylinders, and, in most cases, ellipsoids. For the terrestrial environment, specific exposure conditions are defined for biota that live in and those that live on the soil. For aquatic environments, exposure in the water column, sediment and water-sediment interface are all considered. The geometries, which have been considered, are listed in Tables 5-5 to 5-7.

Calculations of dose conversion coefficients for monoenergetic sources.

Radionuclides in the environment lead to an external radiation exposure of the organism living in or close to a contaminated medium. The external exposures of biota are the result of complex and non-linear interactions of various factors:

- the geometric relation between the source of the radiation and the target;
- the levels of contamination in the environment;

- the materials and their shielding properties in the environment;
- the radionuclide-specific decay properties characterised by the radiation type, the energies emitted and the yield; and,
- the size of the organism.

The geometric relationship between radiation source and the exposed organism is an important factor. The intensity of the radiation field around a source decreases with distance and is influenced by the material between the radiation source and the target. The number of situations is enormous; therefore a number of limited and representative situations have been selected for detailed calculations. The exposure conditions were selected so that they allow the exposures for conditions for which explicit calculations were not made to be determined by interpolation. Table 5-4 summarises the different source-target combinations, in which the habitat of the exposure target is listed against the location of the radiation source.

In the terrestrial environment, with pronounced heterogeneities in materials and densities, analytical approaches are associated with considerable uncertainties. Therefore, Monte Carlo techniques have been used to simulate radiation transport. In the aquatic environment, the difference in densities between the different media (water, sediment) is very low, so the conditions for radiation transport are relatively homogeneous, irrespective of the source-target combination. Therefore, analytical approaches are sufficiently accurate for the aquatic environment.

Table 5-4 Source-target combinations to derive dose conversion coefficients for external exposure.

Exposure target	Radiation source			
	Air	Soil	Water	Sediment
Air	x[7]	x		
Soil surface	x	x		
Soil	(x)[8]	x		
Water			x	(x)
Sediment surface			x	x
Sediment			x	x

Terrestrial environment

For the terrestrial environment, a distinction has been made between species living within the soil and on the soil. Tables 5-5 and 5-6 show the exposure conditions considered for terrestrial animals and plants, respectively. For terrestrial animals, external exposure has been estimated for different thicknesses and depths below the soil surface of the contaminated soil layer.

[7] Source—target combinations that need detailed considerations
[8] Probably not relevant

Table 5-5 Exposure conditions considered for the calculation of dose conversion coefficients for external exposure of reference organisms (animals).

Radiation source	Habitat of exposure target	Radiation type	Target location relative to soil surface (cm)	Source depth (cm)	Energy range (keV)	Target size (m)	Geo-metry
Soil	Soil	β^-		50	10–2000	10^{-4}–10^{-1}	Ellipsoid
		γ	0, –5, –25, –50	0, 5, 10, 20, 30, 40, 50	50–3000		
	Interface soil/air, air	β^-	10^{-2}–1	50	10–2000	10^{-2}–1	
		γ	10^{-2}–10	0, 5, 20	50–2000		

For plants, exposure has been calculated for the meristem and the buds, which are generally the most radiosensitive plant parts. In addition, the distribution of radionuclides in the vegetation canopy is considered differently for the different types of radiation due to their different ranges. For γ- radiation and high energy β-radiation, the whole canopy is considered to be a homogeneously contaminated source of radiation. For α-radiation and low-energy β-radiation, due to the very short range, only the exposure from contamination of the target (internal or external) needs to be taken into account.

Table 5-6 Exposure conditions considered for the calculation of dose conversion coefficients for external exposure of reference organisms (plants).

Plant type	Height (m)	Target organ	Height of plant part considered
Herb	0–0.1	Meristem	At the ground (0 m)
Shrub	0.1–1	Bud, meristem	In middle of canopy (0.55 m)
Tree	1–10	Bud, meristem	In middle of canopy (5.5 m)

The internal exposure due to radioactivity incorporated into an organism is determined by the activity concentration in the organism, the size of the organism, the radionuclide distribution and the kind of radiation and the energy. The set of cases defined for assessment of internal exposure are listed in Table 5-7.

Table 5-7 Energy and geometry specifications for calculations of internal exposures in animals.

Radiation type	Energy range (MeV)	Target size range (m)	Geometry
α	3–10	10^{-5}–10^{-3}	Spheres
β	0.005–4	10^{-5}–0.03	Ellipsoids
γ	0.02–3	0.01–1	Ellipsoids

This set of cases allows the assessment by interpolation of exposure to a wide range of possible species that are not explicitly considered.

The mathematical approaches used to calculate the external dose and internal dose to terrestrial organisms are described in more detail in **[D3]**. The report also includes a tabulation of the external dose from monoenergetic radiation sources for each of the reference organisms and the absorbed fraction of energy due to monoenergetic sources uniformly distributed in the whole body **[D3:AppA, tables A1 to A6]**. These tables can be used for interpolation for organisms not included in the FASSET list of reference organisms.

Aquatic environments

Analytical calculations of dose conversion coefficients for aquatic biota derive were based on the semi-empirical theory by Berger on absorption of photons and electrons [Berger, 1968; 1971], involving the deduction of simple mathematical functions for energy deposition in water by photons and electrons from point isotropic sources, in terms of the “point isotropic specific absorbed fractions”.

Absorbed dose fractions were calculated for each individual ellipsoid using a Monte Carlo calculation, based on Berger’s point specific absorbed fractions, that was repeated for different energies ranging 0.005–1.5 MeV for electrons and 0.015–3 MeV for photons to yield the fraction of energy absorbed within each ellipsoid. The following assumptions were made in the Monte Carlo calculations:

- Organisms are represented as ellipsoids.
- Density differences between the organism and the surrounding media are ignored.
- Radionuclides are distributed uniformly through all tissues of the animal or plant.
- Resulting absorbed doses, both internal and external, are calculated as an average throughout the volume of the organism. This makes most difference in the case of radionuclides in which the external β-component predominates over the γ-component, and (progressively) as the organism becomes larger.
- In calculating the external DCC, it is assumed that the organism is immersed in an infinite absorbing medium with the stated concentration.

Energy absorbed fraction functions were then fitted separately for photons and electrons, as described in **[D3, 4.2]**. The coefficients used to fit the absorbed fraction functions for photons and electrons have been tabulated in **[D3, Table 4.3]** for marine environments and **[D3, Table 4.4]** for freshwater environments.

Calculations of nuclide-specific dose conversion coefficients.

From the DCCs for monoenergetic radiation sources, nuclide-specific DCCs were derived for external and internal exposure, taking into account the type of radiation as well as energy and intensity of the emission.

Radionuclide specific DCCs for external exposure in the terrestrial environment have been tabulated for organisms living on the soil, for planar radiation sources with a surface roughness of 3 mm, and a volume source due to the homogeneous contamination of the upper 10 cm of soil. For organisms living in the soil, it has been assumed that the organisms live in the centre of a homogeneously contaminated layer of a thickness of 50 cm.

Radionuclide-specific DCCs for internal exposure have been derived, assuming a homogeneous distribution of the radionuclide in the organism. Unweighted DCCs for internal exposures are given.

For the aquatic ecosystems, radionuclide specific DCCs were calculated from the absorbed fraction functions.

5.3 Observations/recommendations

5.3.1 General dependencies of the DCCs.

A number of generalisations can be made on the basis of information generated during the development of dosimetric tools, including:

- the dose conversion coefficients for external exposure decrease with the size of the animal due to the increasing self-shielding effect;
- the differences in DCCs for external exposure among organisms are more pronounced for low energy γ-emitters since, for such photons, the effect of self-shielding is more important;
- the exposure to small organisms (*e.g.* mouse) from high-energy photon emitters is higher for underground organisms, compared to aboveground organisms, whereas it is *vice versa* for larger organisms (*e.g.* fox);
- the external exposure to low-energy photon emitters is in general higher for aboveground organisms, since then the shielding effect of the soil is less pronounced;
- for internal exposure to γ-emitters, DCCs increase in proportion to the mass of the organism due to the higher absorbed fractions - this dependence is more pronounced for high-energy photon emitters (*e.g.* 137Cs/137mBa);
- for α- and β-emitters, the DCCs for internal exposure are nearly size-independent.
- for internal exposure, the impact of the radiation quality is especially important for tritium and the α-emitters.

5.3.2 Background exposures

For terrestrial organisms, the external exposure is in the order of 0.1–0.4 mGy per year, depending on size and habitat. The main contributor is ^{40}K. Internal background exposures for terrestrial organisms are more variable. Again, an important contributor is ^{40}K that causes exposures in the order of 0.3 mGy per year. The exposures to muscles and plant tissues caused by uranium, thorium, and radium, lead and polonium are low; however, liver, bone and kidney may be exposed at levels of 0.1 to 1 mGy year^{-1} unweighted absorbed dose. Weighted absorbed doses due to α-emitters are higher in proportion to the weighting factor assumed.

Under specific environmental conditions, much higher internal exposures may be estimated. For example, burrowing mammals receive relatively high lung doses due to the inhalation of radon and its daughter nuclides; animals that graze in Arctic regions may be exposed by ^{210}Pb and ^{210}Po that may be found in high levels in lichens.

For aquatic organisms, the majority of the calculated absorbed dose arises from internally incorporated α-emitters, with ^{210}Po and ^{226}Ra being the major contributors. The dose attributed is therefore closely proportional to the weighting factor assumed for α-radiation. Calculated doses for freshwater organisms are somewhat higher than for marine organisms, and the range of doses is also much greater, reflecting the much greater variability of radionuclide concentrations in freshwater as compared to seawater.

5.3.3 Radiation weighting factors

It is well known that different types of radiation, *e.g.* α-, β-, and γ-radiation, exhibit differing ability to interact with biological material. To account for this different biological effectiveness, the ICRP has introduced a quality factor that compares the effectiveness of the different types of radiation to the effectiveness of irradiation with 300 keV photons. The product of the radiation quality factor and the absorbed dose results in the equivalent dose, which has the advantage to integrate exposures from different radiation types on the basis of the biological effect and not simply on the energy absorbed. The unit of the equivalent dose is the sievert [Sv].

The application of the concept of equivalent dose may be applied to biota only with limitations. The radiation quality factors were derived for the application in dose assessments for humans, for which stochastic effects are primarily important. However, in the assessment of exposures to biota, due to the different endpoints, the emphasis is on the consideration of higher dose levels that may even cause deterministic effects.

Therefore, the radiation quality factors used for the dose assessment to humans may not be applicable to dose assessment for biota. In addition, before the concept of equivalent dose is applied to biota, quality factors have to be derived experimentally for the relevant endpoints.

According to these considerations, the absorbed dose will be the key quantity for the exposure assessment of biota. The estimations made in the framework of this project are made on the base of absorbed dose.

To illustrate the possible impact of the weighting factors of different kinds of radiation, weighted DCCs for the internal exposure of terrestrial animals have been calculated assuming weighting factors of 10 for α-radiation, 3 for low-β radiation ($E < 10$ keV), and 1 for β-radiation with energies above 10 keV and γ-radiation.

It should be noted that, although the radiation weighting factor will have to be incorporated into the assessment at this stage, it originates from effects observations. This is further considered in **[D6, 6.3.2]**.

6 Effects analysis and database

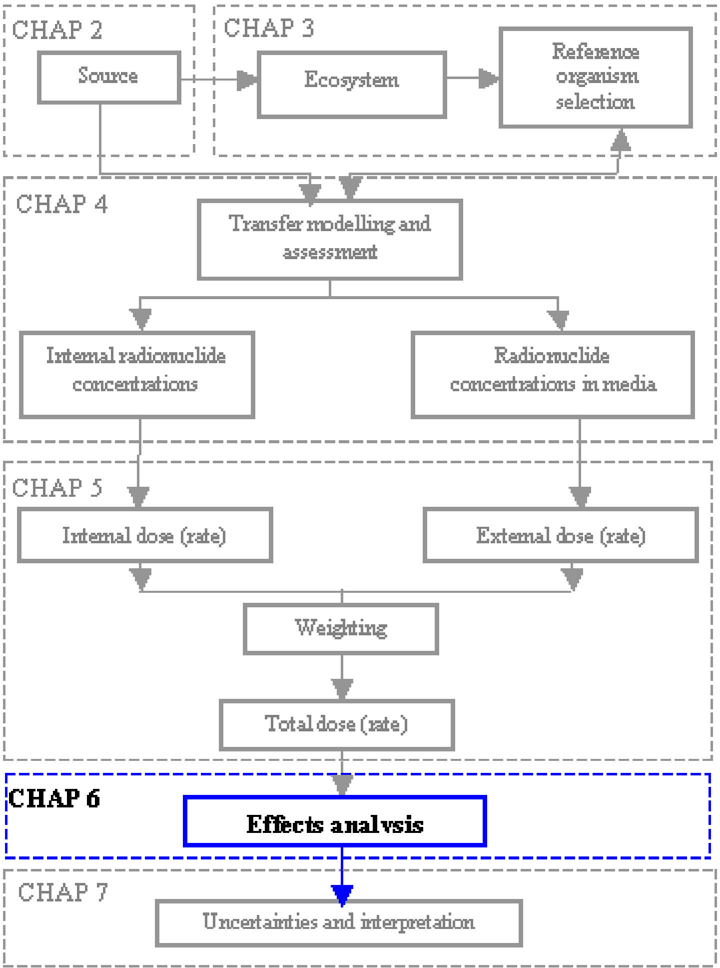

Figure 6-1 Position of the effects analysis within the Framework.

6.1 Introduction

Any system for assessing the impact of a contaminant on the environment requires an analysis of the possible effects on the organisms and ecosystems concerned. The effects analysis must identify:

- relevant biological effects for assessing the impact (the relationship between exposure and effect); and,
- the severity of effects at different levels of exposure (the relationship between the extent of exposure and the degree of response).

The FASSET approach centres the effects analysis on the reference organisms (described in Chapter 3). Since the degree of impact has to be judged against existing information on dose-effect and dose-response relationships, the FASSET project has:

- performed a review of existing data on radiation effects on non-human species; and,

- organised this information in a database to facilitate data retrieval for assessment purposes.

Furthermore, guidance is provided as to extrapolating knowledge where there are knowledge gaps, as well as some guidance to interpreting data. The effects data have been collated in **[D4]**.

6.2 Overview of Framework information and tools

To provide a basis for radiation effects analysis, the Framework compiles data concerning radiation effects, and groups them according to four ‘umbrella’ categories of biological effects of irradiation . These umbrella effects, namely, morbidity, mortality, reproductive success and mutation, were used to aggregate effects data for 16 wildlife groups, those being: amphibians, reptiles, aquatic invertebrates, aquatic plants, bacteria, birds, crustaceans, fish, fungi, insects, mammals, molluscs, mosses/lichens, soil fauna, terrestrial plants and zooplankton. Section 6.2.1 below describe the rationale behind the selection of wildlife groups and umbrella effects.

The data were screened and the selected data collated in a database (in Microsoft Access® 97, and 2000): the FASSET Radiation Effects Database, **[FRED]**. This database collates approximately 25 000 data entries on radiation effects on plants and animals from over 1 000 references. Its structure allows the user to search for information based on wildlife group and umbrella effects, and for acute or chronic exposure to a range of doses or dose rates. FRED is described in more detail in **[D4, 2.1]**.

Data in the FRED have been summarised in tabular form and discussed in **[D4]**, as identified in Table 6-1.

Table 6-1 Data on the effects of radiation on plants and animals.

Information	Appropriate material in [D4]
Overall summary	[D4, 2.2]
Terrestrial plants (including lichen and fungi)	[D4, 2.3.1] and [Table 2-4]
Aquatic plants	[D4, 2.4.1] and [Table 2-5]
Mammals	[D4, 2.5.1] and [Table 2-6]
Birds	[D4, 2.6.1] and [Table 2-7]
Amphibians and reptiles	[D4, 2.7.1] and [Table 2-8]
Soil fauna and bacteria	[D4, 2.8.1] and [Table 2-9]
Insects	[D4, 2.9.1] and [Table 2-10]
Fish	[D4, 2.10.1] and [Table 2-11]
Crustaceans	[D4, 2.11.1] and [Table 2-12]
Molluscs	[D4, 2.12.1] and [Table 2-13]
Aquatic invertebrates and zooplankton	[D4, 2.13.1] and [Table 2-14]

In addition, Deliverable 4 discusses a number of issues related to effects analysis, as listed in Table 6-2.

Table 6-2 Supplementary information to effects analysis.

Information	Appropriate material in [D4]
The relative biological effectiveness of radiation in the context of environmental exposures	[D4, 3]
Extrapolation issues	[D4, 4]
Effects of other environmental stressors	[D4, 5]

6.2.1 Methods – the approach to effects analysis

Exposure regime – implications for the effects analysis

Experimental studies of the effects of ionising radiation on plants and animals are broadly divisible into two categories: those that employ acute exposures (*i.e.* in short periods of time, usually minutes but less than an hour, in comparison with the time taken for an effect to become apparent, and usually at a high dose rate), and those that employ chronic exposures (*i.e.* all of, or a large part of, the life stage of interest, and usually at relatively low dose rates).

The data of greatest use to the FASSET project are clearly those relating to chronic exposures at low dose rates. It is known that the absorbed dose rates likely to occur in environments contaminated by radionuclides released under authorisation are probably less than 0.1 mGy h^{-1}, and almost certainly less than 1 mGy h^{-1} [UNSCEAR, 1996]. However, data appear to be roughly 2:1 biased in favour of acute data, and for chronic data, information on effects at environmentally relevant dose rates, as defined above, is limited.

In a contaminated environment, the radiation exposure to a plant or animal is likely to be from both the external environment, *i.e.* the surrounding air, soil/sediment, or water (mainly γ-rays, but also β-radiation for organisms with dimensions <~ 1 cm), and from internal sources, *i.e.* from α-, β- and γ-emitting radionuclides taken up into the tissues. The source and type of radiation employed in the experimental radiation effects studies have also, therefore, been considered. Because it is known that an exposure from α-radiation (with high Linear Energy Transfer (LET)) is more effective than γ-rays and most β-radiation (low LET), per unit of absorbed dose, in producing biological damage (the Relative Biological Effectiveness, or RBE, phenomenon), any data that might allow an estimate of the RBE value have been noted.

Selection of wildlife groups

The number of species, or even higher taxonomic groupings, for which data were available, was small in comparison with the range of species that might be considered as representative of European ecosystems, for which an impact assessment might be required. As a result, it has been necessary to collate the data into 16 wider wildlife groups, as listed in Table 6-3.

Table 6-3 Framework wildlife groups.

Amphibians	Insects
Aquatic invertebrates	Mammals (non-human)
Aquatic plants	Molluscs
Bacteria	Mosses/lichens
Birds	Reptiles
Crustaceans	Soil fauna
Fish	Terrestrial plants
Fungi	Zooplankton

It is recognised that these wildlife groups are not entirely mutually exclusive in terms of taxonomy, but where overlap occurs, *e.g.* for aquatic invertebrates, crustaceans, soil fauna and zooplankton, this tends to take account of the routes and/or sources of radiation exposure. The restricted number of groups adopted also takes into account the limited availability of information for each group from which generalisations concerning the dose (rate) – response relationships may be developed.

Appropriate level of biological organisation and umbrella effects

Most gathered data centred on the effects of ionising radiation on individuals, but *e.*related to an enormous number of differing biological responses or endpoints. Again, therefore, it was necessary to develop some rational basis for categorising the information for the purpose of the Framework.

As a primary objective of the assessment system is to provide for an acceptable degree of protection for the non-human living environment, a decision was required as to whether this meant protection of all individuals or of the populations of which they were constituent members. The Framework concluded that there were two main factors contributed to describing effects of ionising radiation at the individual level.

First, the initial interaction of ionising radiations with biological tissue is, through the production of reactive ions and radicals, the disruption of biomolecules, particularly the nuclear DNA, and the biochemical processes within a cell. This may lead to immediate or delayed cell death, or - through complete or incomplete repair processes - to survival as a normal or mutated cell. The loss of a few cells (at low dose rates or accumulated doses) will have little effect on most tissues, particularly if the normal homoeostatic processes of cell replacement can make up the deficit, but at higher dose rates and accumulated doses there may be a degradation of tissue or organ function and, ultimately, a reduction in the fitness of the individual that influences its survival and/or reproductive capacity. These latter attributes may also be influenced by the accumulation of mutations in somatic tissues with the possible outcome of cancer. Mutations in germ cells can influence reproductive capacity through reduced gamete production, reduced viability of resulting embryos and reduced fitness of surviving offspring. It is clear, therefore, that radiation can induce a variety of responses in individual organisms that are amenable to quantification.

The second factor relates to the available information – almost all of it concerns effects on individual organisms; there are rather few data concerning effects of radiation on that can be quantified only at the population level. It is clear, nevertheless, that the various effects of radiation in individuals may, through their aggregated impact on reproductive capacity, have an effect at the population level. It seemed helpful, therefore, to organise the information on radiation effects on individual organisms into umbrella categories that were relevant to possible responses at the population level, *i.e:*

- 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 an entity separate from its parents); and,
- mutation (induced in germ and somatic cells).

Organisation of effects data – FASSET Radiation Effects Database (FRED)

References to over 200 000 articles published in the last 50 years were found by database searches. Major reviews [*e.g.* UNSCEAR, 1996; IAEA, 1992] were also used as starting points for information collection. In order to make the data collation exercise manageable, a number of selection criteria were applied:

- Only those data relevant to the requirements of the FASSET project were included. Expert judgement was used to determine the degree of relevance. Data published before 1945 were excluded.
- Data derived from studies of, or for application to, human radiobiology, *e.g.* studies of high dose, high dose rate responses of particular tissues for application in the design of radiotherapy treatment schedules, were not included.

The radiation effects data were collated in a structured manner, according to the four umbrella endpoints, 16 wildlife groups, and exposure regime (acute *vs*. chronic). Data were collated at species level.

In addition to the bibliographic information and these three main categories, there was a requirement to record, where possible, the type and source of radiation, the dose rate and total dose, the lowest dose or dose rate at which an effect was observed (LOED and LOEDR, respectively); the highest dose or dose rate at which no effect was observed (HNED and HNEDR, respectively); information on the actual biological endpoints recorded in the study; and an indication of whether the data could be used to determine an RBE value.

6.2.2 Summary of database information

In the context of environmental protection, chronic radiation exposures, rather than acute, are of greatest importance, therefore this Section will concentrate on the collated data from chronic effects. An overall summary from FRED of the chronic effects data for the different wildlife groups is shown in Table 6-7. For chronic exposures the largest number of references exists for plants, fish and mammals. Conclusions regarding these three groups, are therefore also considered in more detail below.

Plants

A summary of the database for plants is shown in Table 6-4. The studies in the database reveal that woody plants (*Gymnosperms*) belong to the most radiosensitive species while *Cryptogams* are the most radioresistant. One important determinant of the radiation response is the plant life form, which may give differential shielding of sensitive parts. Size, shape and the density of plant stands may alter the exposure and consequently the radiation dose. Species with exposed meristems or buds may receive much higher dose to critical tissues than plants with underground growth and reproduction or those protected by thick scales.

The data reported relate mostly to the endpoints of reproductive capacity and mutation. It is known that the development affects the end point studied. The dry seed is most radioresistant while the gametogenic cells at meiosis are most sensitive. Polyploidy, common in species that survive in extreme environments, yields greater radioresistance, and in addition these plants usually have vegetative reproduction. Environmental factors, *e.g.* temperature, light and competition, influence the degree of response caused by radiation. This may render comparisons between different field experiments difficult.

Data reported on radiation effects on coniferous forest and deciduous trees show increasing radioresistance as follows: coniferous trees, deciduous trees, shrubs and herbaceous plants. The most important cereal crops (wheat, barley, rye, maize, and rice) vary appreciably in sensitivity. The legumes studied such as pea, pepper, broad bean, horse bean, soybean and red kidney bean, have sensitive stages. Data also include root and vegetable crops, miscellaneous fruits and cotton.

Numerous works report the existence of adaptive responses and also higher genetic effectiveness (point mutations) per unit absorbed dose at lower dose rates than at higher ones.

Fish

A summary from FRED data on fish is shown in Table 6-5. It can be concluded that chronic exposures at dose rates up to 4 mGy h^{-1} of developing embryos (most sensitive stage) will not have significant effects on subsequent growth. Minor anomalies, such as opercular defects, have been increased by 0.2 mGy h^{-1} in salmon and these may affect later survival. Conflicting results for effects on the immune system showed that for rainbow trout irradiated as embryos there was a threshold for effects between 8.3 and 83 µGy h^{-1} of ^{3}H β-radiation, while for ^{137}Cs there was no effect at 9 mGy h^{-1}. The limited data available on mortality effects of chronic irradiation, indicate that dose rates $<$4 mGy h^{-1} at any life stage are unlikely to affect survival. There is little consistent, significant evidence for any effects on reproductive capacity at dose rates $<$0.2 mGy h^{-1}. However, there is probably not a threshold for some endpoints, *e.g.* GSI, number of gametogenic cells in fish irradiated as embryos. Very limited data suggest that chronic irradiation-induced genetic damages probably occur at all dose rates and that radiation sensitivity for this damage is similar to that of other vertebrates.

Table 6-4 Effects of chronic irradiation on plants.

Dose rate ($\mu Gy\ h^{-1}$)	Species	Radiation	Effects described	Umbrella effect
100–1 000	Pine	Gamma	Reduced trunk growth of mature trees.	Morbidity
			Death of some conifers; little changes in populations.	Mortality
(1–5) x 10^3	Pine	Gamma	Reduced canopy cover of individual conifers; whole canopy remains constant.	Morbidity
			Decreased stem growth of saplings.	Morbidity
			Reduced photosynthetic capacity of pines and thus growth.	Morbidity
(5–10) x 10^3	Pine	Gamma	Death of all conifers within 2–3 years.	Mortality
(10–20) x 10^3	Pine	Gamma	Reduced seed production and germination.	Reproduction
			Morphological changes in leaves of some plants.	Morbidity
			Withered crowns.	Morbidity
	Birch	Gamma	Under developed leaves.	Morbidity
>20 x 10^3	Herbaceous	Gamma	Reduced reproductive potential.	Reproduction
	Birch	Gamma	Death of trees.	Mortality
	Grasses	Gamma	Death of grasses and forbs.	Mortality
>100 x 10^3	Plants	Gamma	Death of all higher plants.	Mortality
>1,000 x 10^3	Lichen	Gamma	Reduced diversity of lichen communities after 1 year exposure.	Mortality

Mammals

A summary from FRED for mammals is shown in Table 6-6. Considering the data available on the effects of chronic irradiation on non-human mammals it can be concluded that dose rates lower than 1mGy h^{-1} do not produce clear irreversible effects on morbidity, mortality or reproductive capacity of this wildlife group. Significant reduction in lifespan was seen in several species of mammals at dose rates above 1 mGy h^{-1}. A threshold of ~0.1mGy h^{-1} has been described for reproductive capacity impairment, although the detrimental effects are reversible. There are too few data to draw conclusions on mutation effects of chronic irradiation on mammals. The main gaps in information for mammal species is the lack of data on the effects that exposure to α emitters, via inhalation or ingestion, could have on mortality, morbidity or reproductive capacity. Finally, since most of the studies have been done using mice and rats, it would be useful to have additional information on the effects induced by chronic irradiation in other mammalian species.

Table 6-5 Effects of chronic irradiation on fish.

Dose rate (μGy h^{-1})	Species	Radiation	Effects Described	Umbrella effect
100–1 000	Plaice, Medaka, Roach	Gamma	Reduction in testis mass and sperm production. Lower fecundity. Delayed spawning.	Reproduction
(1–5) x 10^3	Plaice, Eelpout, Medaka, Guppy, Rainbow trout	Gamma, Beta	Reduction in testis mass and sperm content. Severe depletion of spermatogonia. Reduced fertility or complete infertility. Reduced fecundity. Reduced male courtship activity Reduced immune response	Reproduction Morbidity
(5–10) x 10^3	Medaka	Gamma	Depletion of spermatogonia.	Reproduction
(10–50) x 10^3	Medaka, Guppy	Gamma	Sterility. Reduction in larval survival Increase in vertebral anomalies.	Reproduction
>50 x 10^3	Guppy	Gamma	No impact on offspring survival following parental irradiation.	Mortality

Table 6-6 Effects of chronic irradiation on mammals.

Dose rate (μGy h^{-1})	Species	Radiation	Description	Umbrella effect
<100	Mouse, Rat	Gamma, Beta	No detrimental effects have been described.	Morbidity Mortality Reproduction
100–1 000	Dog	Gamma	Life shortening.	Mortality
	Mouse	Gamma	Life shortening.	Mortality
	Mouse	Neutrons	Life shortening.	Mortality
	Pig	Gamma	Prenatal irradiation decreased the number of primitive stem germ cells and the ovary and testis weight.	Reproduction
	Rat	Gamma	Reduction in number of A1 spermatogonia.	Reproduction
	Mouse	Beta	Irradiation from conception to 14 days of age decreased the number of primary oocytes.	Reproduction
	Mouse	Gamma	Reduction of mean number of litters per female; higher mortality between birth and weaning; reduction in number of primary oocytes.	Reproduction
			Irradiation during 3 consecutive generations increased the % of sterile mice and the % of early deaths and decrease the mean litter size.	Reproduction
			Field study. Increased % of sterile pairs; reduced mean offspring sired and weaned.	Reproduction
	Reindeer	Gamma	Natural forest. Increased number of chromosomal aberrations.	Mutation

Table 6-6 (cont'd) Effects of chronic irradiation on mammals.

Dose rate ($\mu Gy\ h^{-1}$)	Species	Radiation	Description	Umbrella effect
$(1–5) \times 10^3$	Goat	Gamma	Life shortening.	Mortality
	Mouse	Gamma	Increased mortality ratio (the effect was dependent on the mice strain used); decreased mean after survival.	Mortality
	Mouse	Neutrons	Life shortening.	Mortality
	Goat	Gamma	Reduced number of born per female in the third generation and reduced total sperm production.	Reproduction
	Mouse	Gamma	Irradiation during the 2nd week after birth reduced the fertility and the litter size.	Reproduction
			Irradiation during 4 to 90 days reduced the fertility span, the germ cells per ovary and the testis weight.	Reproduction
	Rat	Beta	Prenatal irradiation reduced the litter size and increased the % of resorptions.	Reproduction
	Rat	Gamma	Reduced number of spermatogonia and testis weight.	Reproduction
			Prenatal irradiation reduced the number of germ cells in females and males.	Reproduction
	Mouse	Gamma	Increased mutation frequency at seven specific loci in mouse spermatogonia.	Mutation
$(5–10) \times 10^3$	Sheep	Beta	Reduction in the number of leukocytes in peripheral blood.	Morbidity
	Rat	Gamma	Reduced brain weight and cingulum volume.	Morbidity
	Mouse	Gamma	Life shortening after exposures of 68 days or longer.	Mortality
			Increased paternal expanded simple tandem repeat (ESTR) mutation rate and paternal mutation per offspring band at loci MMS10 plus Ms6-hm plus Hm-2.	Mutation
$>10 \times 10^3$	Dog	Beta	Reduced survival.	Mortality
	Mouse	Gamma	Increased mortality ratio (dependent on the strain used).	Mortality
	Rat	Gamma	Prenatal irradiation reduced the length and weight of embryos and increase the % mortality.	Reproduction
			Reduction in ovary and testis weight.	Reproduction

Table 6-7 Summary of the chronic effects data for the wildlife groups, based on the FASSET Radiation Effects Database, FRED

Wildlife Group	Reference Organisms	Morbidity	Mortality	Reproductive capacity	Mutation
Amphibians	Amphibians	Too few data to draw conclusions.	No data available.	No data available.	Too few data to draw conclusions.
Aquatic invertebrates	Benthic invertebrates 'Worms'	No data below 10^3 µGy h^{-1}. No effects on worm growth at 1.7 10^3 µGy h^{-1}. Limited data to draw conclusions.	Dose rate dependent effect on worm survival above 1.7 10^3 µGy h^{-1}. Too few data to draw conclusions.	Too few data to draw conclusions. Out of five references, only one listed two LOEDR for dose rate > 10^4 µGy h^{-1}, and an HNEDR of 190 µGy h^{-1} for *Neanthes arenaceodentata*.	Too few data to draw conclusions.
Aquatic plants	Vascular plants Macroalgae Phytoplankton	Too few data to draw conclusions.	Too few data to draw conclusions.	No data available.	No data available.
Bacteria	Soil micro-organisms Benthic bacteria	Too few data to draw conclusions.	No data available.	No data available.	No data available.
Birds	Wading birds Birds	No data available.	No data available.	Only six references were recorded, with data on a wide range of dose rates. Conclusive dose-effects relationships could be drawn for chicken for dose rates > 10^4 µGy h^{-1}.	Too few data to draw conclusions.
Crustaceans	Crustaceans	No data for low chronic exposures. Only three references were recorded, with all dose rates > 10^4 µGy h^{-1}.	No data on low chronic exposures. Only three references were recorded, with all dose rates > 10^4 µGy h^{-1}.	No data for low chronic exposures. Only three references were recorded, with all dose rates > 10^4 µGy h^{-1}.	No data available.
Fish	Fish eggs Fish	One experiment, but not another, indicates effects on immune system at <8.3 µGy h^{-1}.	Too few data to draw conclusions.	One study showing effects on gametogenesis at 230 µGy h^{-1}. Otherwise effects at > 10^3 µGy h^{-1}.	Radiation exposure increases the mutation rate.
Fungi	Fungi	Too few data to draw conclusions.	No data available.	No data available.	No data available.
Insects	Canopy invertebrates Soil invertebrates	Only seven references were reported with no experiments below 500 µGy h^{-1}. Only two described effects under gamma exposures for wide ranging dose rates, all above ~10^3 µGy h^{-1}.	No data on low chronic exposures. Only one reference was reported, with all dose rates > 10^4 µGy h^{-1}.	Too few data to draw conclusions.	Too few data to draw conclusions. Only two papers for dose rates > 10^4 µGy h^{-1}.
Mammals	Sea mammals Burrowing mammals Herbivorous mammals Carnivorous mammals	Rat growth not affected at 16 µGy h^{-1} but affected at >3 10^3 µGy h^{-1}. Some blood parameters affected at 180-850 µGy h^{-1}. No effect on thyroid function at 9 10^3 µGy h^{-1}.	No effect on mouse lifespan at 460 µGy h^{-1}, but significant reductions above ~10^3 µGy h^{-1} in the mouse, goat and dog.	Threshold for effects at ~100 µGy h^{-1}, with clear effects at >10^3 µGy h^{-1}.	Too few data to draw conclusions. One of nine references gives an LOEDR of 420 µGy h-[1] for mice.

Wildlife Group	Reference Organisms	Morbidity	Mortality	Reproductive capacity	Mutation
Molluscs	Molluscs	Too few data to draw conclusions. One of the two reported references gives an LOEDR of > 10^4 µGy h-$^{-1}$ for *Physa heterostrophaone*.	Too few data to draw conclusions. Two references reported, both with LOEDR of > 10^4 µGy h-$^{-1}$ for *Mercenaria mercenaria*, and *Physa heterostrophaone*.	Too few data to draw conclusions. One of the two references gives an HNEDR of 10^4 µGy h-$^{-1}$ and an LOEDR > 10^4 µGy h-$^{-1}$ for *Physa heterostrophaone*.	No data available.
Moss/Lichens	Bryophytes	Too few data to draw conclusions.	No data available.	No data available.	No data available.
Plants	Plants Grasses Herbs and crops Shrubs Tree	Plant growth begins to be affected at >100 µGy h^{-1}. Continued exposure at 21 µGy h^{-1} for 8 years increases the sensitivity in pines.	50% mortality at 8 years at ~10^3 µGy h^{-1} in pines.	A field study indicated a decrease in seed weight of a herb at 5.5 µGy h^{-1}.	The mutation rate in micro-satellite DNA increased at ~40 µGy h^{-1}.
Reptiles	Reptiles	No data available.	No data available.	No data available.	Too few data to draw conclusions.
Soil fauna	Soil micro-organisms Soil invertebrates 'Worms'	Too few data to draw conclusions.	Too few data to draw conclusions. One of nine references gives an LOEDR of > 10^4 µGy h^{-1} for various species.	No data available.	Too few data to draw conclusions.
Zooplankton	Zooplankton	Too few data to draw conclusions.	No data available.	Too few data to draw conclusions. The only reported reference gives an LOEDR of 440 µGy h^{-1} for *Tetrahymena pyriformis*.	No data available.

6.3 Observations and recommendations

6.3.1 General observations

The work undertaken within the FASSET project, on effects of irradiation on plants and animals, has highlighted the fact that the available information on the effects of low dose rates, in continuous irradiation (< 1mGy h^{-1}), is reasonable for plants, fish and mammals, but is scarce or non-existent for other wildlife groups.

The fragmentary nature of the available, and relevant, information has made it very difficult to develop the desired dose rate - response relationships in any detail. Some very broad and general conclusions may, however, be drawn:

- although minor effects may be seen at lower dose rates in sensitive species and systems, *e.g.* haematological cell counts in mammals, immune response in fish, growth in pines, and chromosome aberrations in many organisms, the threshold for statistically significant effects in most studies is about 0.1 mGy h^{-1}; the responses then increase progressively with increasing dose rate and usually become very clear at dose rates >1mGy h^{-1} over a large fraction of the life-span;
- there are, however, some data that do not fit too comfortably within this broad generalisation, *e.g.* the effects of tritium β-radiation on the developing immune response in fish embryos, on the developing goose barnacle embryo, and also, perhaps, on the developing oocytes in embryonic and neonatal mice; and,
- the significance for the individual, or for the population more generally, of the minor responses, particularly in terms of morbidity and cytogenetic effects, seen at dose rates less than 10^2 µGy h^{-1} has yet to be determined.

The FRED database has highlighted where data are most abundant, and provides direction to fill in gaps where scientific information is missing. It can be concluded that for all the wildlife groups considered, including plants, fish and non-human mammals, the studies on the potential detrimental effects of ionising radiation have been done under experimental conditions, that mostly do not reflect the situation that would occur after radioactive contamination of the environment. This is true not only in relation with the doses and dose rates used, but also in relation to the type of radiation, exposure conditions, endpoints and species used in the studies. Therefore, it will be crucial in future research activities to carefully plan experiments in order to obtain useful results for environmental protection purposes.

6.3.2 Influence of radiation quality

A longstanding problem relates to the treatment of radiation exposures from radiations of differing quality, *i.e.* differing energy deposition rates along the particle track or linear energy transfer (LET). It is known that radiations having a high LET are more effective in generating damage, per unit of absorbed energy, than radiations of low LET - the relative biological effectiveness (RBE). In the context of an environmental assessment, this mainly relates to exposures from internal contamination with emitters of α-particles, *e.g.* ^{239}Pu and ^{241}Am, or β-particles with energy less than 10 keV, *e.g.* tritium (it should be noted that this concern also applies to the exposures from the natural background). The use of radiation weighting factors, w_R, to take account of this influence of radiation quality on the biological effects of radiation, should be as applicable for non-human organisms as it is in the case of human radiological protection dosimetry.

The database tags papers that give information that may be of use in estimating RBE values. Altogether, there are 78 papers in FRED that have been identified, of which 65 have been useful for the Framework, which relate mainly to mammals. As a consequence, there are too few data to make a recommendation for appropriate radiation weighting factors for the umbrella endpoints, wildlife groups and dose rates of interest for the Framework. Nevertheless, there are reasonable grounds for concluding that the RBE for α-particles is unlikely to be greater than ~200, and lower than ~5 for low energy β-particles. As an interim measure, the FASSET Framework recommends that, in order to demonstrate the influence that radiation quality might have on the estimation of the biologically effective dose rate, radiation weighting factors of 5, 10 and 50 could be applied in the calculation of nuclide-specific dose conversion factors for internal sources of α-particles.

See also **[D6, 5,3,3]** for an account of this issue.

6.3.3 Extrapolation issues

In view of the relative paucity of relevant radiation effects data, the question arises as to whether it is possible to make extrapolations to fill some of the data gaps. As mentioned, the radiation effects data included in the database are heavily weighted (2:1) towards acute high dose exposures. Although there is considerable evidence that low dose and dose rate, chronic irradiation exposures are generally less damaging than high dose and dose rate, acute exposures, there does not appear to be a robust, and generally applicable, basis for extrapolation between these two contrasting exposure conditions. For the present, therefore, the Framework must depend on the more limited information in the database relating to low dose and dose rate exposures.

From the summaries of data from the database, it was concluded that the relatively large differences in radiosensitivity between the taxonomic groups that are seen in the responses to acute irradiation, particularly in terms of the LD_{50} values, become less pronounced for continuous, low dose rate radiation exposure, and particularly for endpoints other than mortality. Nevertheless, there remain substantial differences in radiosensitivity between taxonomic groups, and between the different life stages of a given species, and there is no generally valid basis for making extrapolations.

A very few attempts have been made to integrate the available information concerning the effects of radiation in individuals into an assessment of possible responses at the population level. These appear to indicate that measures intended to limit the radiation effects on mortality and reproductive capacity in individuals will also provide a sufficient degree of protection for populations. In addition, the few experimental studies with water fleas (*Daphnia pulex*) indicate that the levels of chronic radiation exposure ($< \sim 0.1$mGy h^{-1}) expected from regulated waste management activities will not affect population parameters.

6.3.4 Other environmental stressors

There is abundant evidence that other environmental variables, within their natural range of values, interact with radiation exposure to influence the response observed in organisms, and that radiosensitivity is likely to be increased if the environmental conditions move from the optimum. In respect of radiation interactions with other contaminants, there are too few data to draw any general conclusions.

6.3.5 Future of database

The FASSET Radiation Effects database will be maintained on www.fasset.org, and will be extended within the ERICA project (www.erica-project.org) to incorporate new and previously not included data; an example of the latter is data presently aggregated within the database built up within the EPIC project.

7 Uncertainties and interpretation

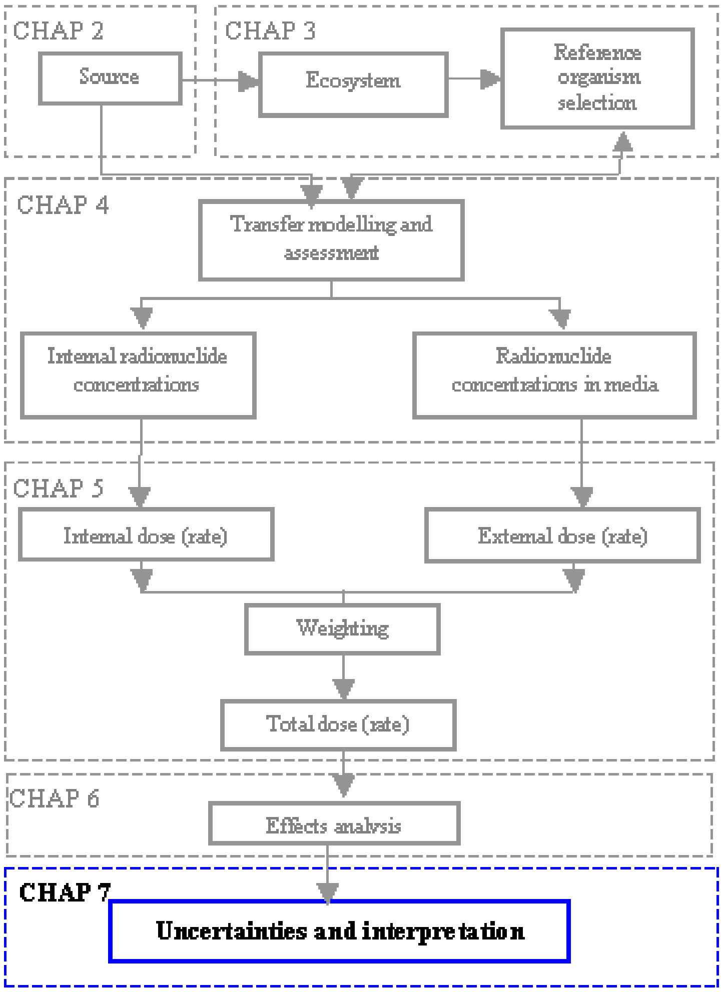

Figure 6-1 Position of general uncertainty analysis, and interpretation of effects in a wider environmental context, within the Framework.

7.1 Introduction

The assessment endpoint of the Framework is the estimation of effects in individual organisms, based on tools developed for reference organisms and selected wildlife groups. A number of factors need to be considered in relation of such estimates:

- the uncertainties associated with the estimates (conceptual uncertainties in the models applied, uncertainty in the values of the model parameters, uncertainties in the empirical data due to natural variability, measurement errors, biases in sampling and monitoring, and uncertainties associated with the lack of data or information); and,
- the environmental significance of the estimate, which may include consideration of the magnitude of effects, size of affected area, and – if such values are available - on how the estimated values (*e.g.* environmental concentration, dose rates, species composition) compare with the reference values used for risk characterisation.

The estimates of effects, as well as their associated uncertainties, underpin the prioritisation of environmental risks associated with a particular source, as part of the risk characterisation stage of a full assessment (*cf*. Figure 1-1). This stage includes the identification of aspects of concern, which will guide managerial actions, taking into consideration that radiation may be one out of several hazards associated with the specific source.

The development of a rigorous methodology for characterising risk was outside the scope of the FASSET project. However, some information relevant to uncertainties, as well as methods for extrapolation of existing data to areas where data are absent, has been indicated in previous chapters. In addition, two examples of application of the exposure assessment methodology are described in **[D5]**, where uncertainty analyses are performed.

7.2 Overview of FASSET information and tools

The Framework contains information relevant to uncertainties, data gaps and subsequent interpretation in a wider environmental context in a number of instances. The sources to this information are summarised in Table 7-1.

7.3 Observations/recommendations

The Framework is based on the use of measured data from traceable sources for European ecosystems, as well as on the literature data on effects with emphasis on data considered relevant for the purpose of developing the Framework. Quality checks have been carried out on the data. Where data are insufficient, a reasonable degree of caution should be adopted, accompanied by clear statements about the assumptions made and the introduced uncertainties.

Data origin, uncertainties and constraints associated with the data must be stated for transparency. In addition, data assumptions made during the assessment must be clearly documented.

Since effects of radiation are related to the total dose, *i.e.* including the background, and since the dose-response relationships in many instances are non-linear, assessments of environmental impact need to consider background separately.

The following general advice in managing uncertainties and interpretations can be given.

- State openly where there are gaps.
- Consider the sensitivities involved in the assessment. For some organisms and for β- and γ-emitting radionuclides, the total dose to the organism is likely to be dominated by external radiation: a transfer factor should/will then have to be set at a very high value, in order for internal radiation to make a significant contribution to the total dose. In some cases, it may be possible to show that the internal contribution can be ignored. The position may be different for alpha emitters.

Table 7-1 Sources of information relevant to the treatment of uncertainty and interpretation, in Framework documentation.

Issue	Details	Documentation
General advice and observations on data requirements and uncertainty	Observations from other Frameworks, in particular BIOMASS, FASSET approach	[D2:1, 4], [D2:2, 10], [FASS/BIOM]
Data gaps in transfer assessment	General recommendations	[D5, 3.5]
Uncertainties in transfer assessment	Probability distributions and parameter ranking	[D5, 3.6]
Transfer factors	For different reference organisms and nuclides, ranking of confidence in three categories: “high”, “medium” and “low”	[D5: App.1, 1]
Assumptions underlying derivation of dose conversion coefficients		[D3]
Data gaps in effects data	Tabular extraction of available information, and database	[D4, 2], [FRED]
Relative biological effectiveness and weighting factors	Discussion on available data and recommended ranges	[D3, 2.4], [D4, 3]
Extrapolation of effects data	Extrapolation from acute to chronic, and from individual to population	[D4, 4.2 – 4.4]
Other stressors	Modifying effects on radiation induced effects	[D4, 5]
Examples of the application of exposure assessment methodology	One marine and two terrestrial ecosystems	[D5, 5]

- A maximum value may be chosen for a particular missing transfer factor. By running an assessment under the FASSET Framework using that default value, one should be able to establish whether there may be a problem with the calculated internal dose to the organism, and thus be a need to re-define the transfer factor value more realistically.
- Consider the biological effects database (FRED) and apply expert judgement to the significance of the (potential) effects within a wider (usually involving extrapolation to population and ecosystem levels) environmental context. If necessary, go back to the original publications, which are of most relevance.
- Consider assessment results in relation to environmental standards or guidelines, if in existence, and in relation to protective legislation.

8 References

All FASSET reports are listed in Table 1-1.

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