# Estimation of radioecological sensitivity

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**Abstract.** After the release of radionuclides into the environment it is important to be able to readily identify major routes of radiation exposure, the most highly exposed individuals or populations and the geographical areas of most concern. There have been significant recent improvements in our capability to estimate spatial variation in the environmental behaviour of radionuclides through better understanding of the underlying processes and an ability to spatially apply this knowledge by integrating relevant spatial information in the form of digital data sets using geographical information systems. Thus, it is now possible to refine the estimation of spatial variation in radiation exposure, both for routine releases and in accident situations. Within a recent EC-funded concerted action (the Radioecological Sensitivity Forum), there has been a renewed consideration of the concept of radioecological sensitivity with a particular focus on identifying sensitive areas as well as processes and communities. The concept should be relevant for both terrestrial and aquatic ecosystems, and might even be applied for consideration of doses to biota, although the current focus has been restricted to a consideration of human exposure. The conclusions of the action are outlined, considering the potential usefulness of the concept, and methods by which it can be applied. A framework for the estimation of radioecological sensitivity is proposed and the various measures by which it can be considered, including (i) aggregated transfer coefficients, (ii) action loads, (iii) fluxes and (iv) individual exposure of humans are discussed. The importance of spatial and temporal consideration of each of these outputs is emphasized.

## 1. INTRODUCTION

Certain components of ecosystems accumulate large amounts of radionuclides; such accumulations vary with radionuclide and type of ecosystem. For some radionuclides (especially Cs, Sr and I isotopes), there is now a good understanding of the underlying environmental factors leading to high exposure of humans and also improved information on variation in dietary and social habits. Furthermore, we know that these factors can vary both spatially and temporally, and that this can be important in determining individual doses. Many post Chernobyl studies have demonstrated that the highest exposures do not necessarily coincide with the most contaminated areas, especially in the mid-long term after an accident.

A consideration of time and space can therefore help to identify not only the key exposure routes, but also the locations where high exposure will occur and where it will be sustained for longer periods after contamination occurs. These analyses have been facilitated by the increasing use of geographical information systems combining dynamic models with spatially varying information. This has in turn prompted a reconsideration of the concept of radioecological sensitivity, which was first proposed by Aarkrog [1], who outlined an approach to estimating radioecological sensitivity in a study quantifying doses arising from global fallout of $^{137}Cs$ and $^{90}Sr$ in Denmark and the Faroe Islands.

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The concept of radioecological sensitivity has been considered with a particular focus on identifying sensitive areas as well as processes and communities in both terrestrial and aquatic ecosystems [2]. There is the potential to consider sensitivity with respect to doses to biota, but the focus has thus far been restricted to a consideration of human exposure. The conclusions of this EC-funded work (below referred to as the forum) are outlined considering methods by which the concept can be applied and its potential usefulness.

## 2. REQUIREMENTS FOR SENSITIVITY ANALYSIS

For most pollutants, sensitivity (or vulnerability analysis) has become an important area of assessment and is considered with respect to the effects of pollutant input on various aspects of ecological functioning such as biochemical, physiological, morphological and behavioural responses. The focus here is on the assessment of effects related to radiation dose.

Radioecological sensitivity thus needs to consider the extent to which an ecosystem contributes to an enhanced radiation exposure to Man and/or biota. The definition of radioecological sensitivity should be as broad and generically applicable as possible because many different factors can influence the exposure. However, at the same time, the concept should also be useful in a site specific context. Some factors are generically applicable to all radioactive contaminants whereas others would be relatively more important for just a few radionuclides. Radioecological sensitivity should be applicable to practices as well as interventions, although the application differs for these two situations. For practices, the radioecological sensitivity of an area or ecosystem can be taken into account as part of pre-planning and an optimisation procedure of a particular source. For accidents, knowledge about radioecological sensitivity can assist in identifying priorities (eg. concerning which exposure pathways should be considered in different areas with time and the implementation of countermeasures) after an accident has occurred. Ideally, radioecological sensitivity can be introduced as part of emergency preparedness.

The radioecological sensitivity concept is applicable to all radionuclides, but sensitivity is radionuclide specific. Depending on the scenario the radionuclides of concern varies. The concept should be applicable to all sources, and should also be able to incorporate natural radionuclides of concern such as $^{210}Po$ and U.

Enhanced exposure can arise for a number of different reasons:

- high radionuclide accumulation (eg. high biomass concentration, high precipitation rates, proximity to radiation sources such as nuclear plants, mining activities and waste disposals)
- sustained retention in certain environmental compartments (long biological or ecological half-lives [3]
- high bioavailability leading to significant trophic level transfer (eg. high uptake from soil),
- interaction with ecosystems (dietary habits, occupancy habits, agricultural practices).

Radioecological sensitivity in ecosystems can be measured in terms of different exposure routes to humans, including internal exposure from ingestion, inhalation and external exposure. The forum focused on ingestion dose, but some of the criteria considered would also be relevant to the other routes.

## 3. MEASURES OF RADIOECOLOGICAL SENSITIVITY

The objective is to define the appropriate quantities necessary to define radioecological sensitivity and to consider their temporal and spatial variation. Aarkrog defined *Radioecological Sensitivity* as "the infinite time-integrated radionuclide concentration in the environmental sample considered, arising from a deposition of 1 mCi km$^{-2}$ of the radionuclide in question." This definition is further elaborated in the Introduction of the report as "The radioecological sensitivity of a sample is the infinite time integral of appropriate quantities of the sample from an appropriate quantity of the radionuclide deposited. The radioecological sensitivity equals the steady state concentration in the sample of the radionuclide considered from a constant annual deposition rate of the radionuclide distributed like global fallout throughout the year." Finally, in his Concluding Remarks Aarkrog states that "In this study radioecological sensitivity has been defined as the transfer factor from deposition to the environmental sample". Thus, Radioecological Sensitivity, as used by Aarkrog, is related to the quantity, commonly used (in particular in the former Soviet Union) to describe environmental transfer, namely the *Aggregated Transfer Coefficient (Tag)* and, from earlier statements, includes an infinite time integration.

The consensus viewpoint was that the general approach proposed by Aarkrog was useful. However, the forum felt that other indicators for radioecological sensitivity analysis would also be valuable, and, furthermore that it was important to introduce flexibility regarding the length of time considered for assessment, variations in deposition rates and concentrations, and a spatial context. Overall, the conclusions from forum discussions on methods of assessing and quantifying radioecological sensitivity are summarised in Figure 1. Four quantities or indicators were identified, three of which have been commonly used in radioecology or radiation protection, namely aggregated transfer coefficients, fluxes and individual exposure of humans. In addition, a fourth quantity, the action load, was identified as a useful sensitivity measure for short timescales.

These four quantities (in boxes in Figure 1), are each influenced or defined by different processes or factors (shown in the oval boxes) and each relate directly to the amount of radionuclide present (Bq $m^{-2}$). For each of these quantities, both temporal and spatial variability need to be considered. Temporal considerations are potentially important and need to be considered from three perspectives: (i) physical half-lives of radionuclides (ii) biological half-lives in various ecosystem components and (iii) ecological half-lives in different ecosystem compartments and types of ecosystems. Spatial variability will depend on variation in both ecosystem characteristics and human utilisation of terrestrial and aquatic resources.

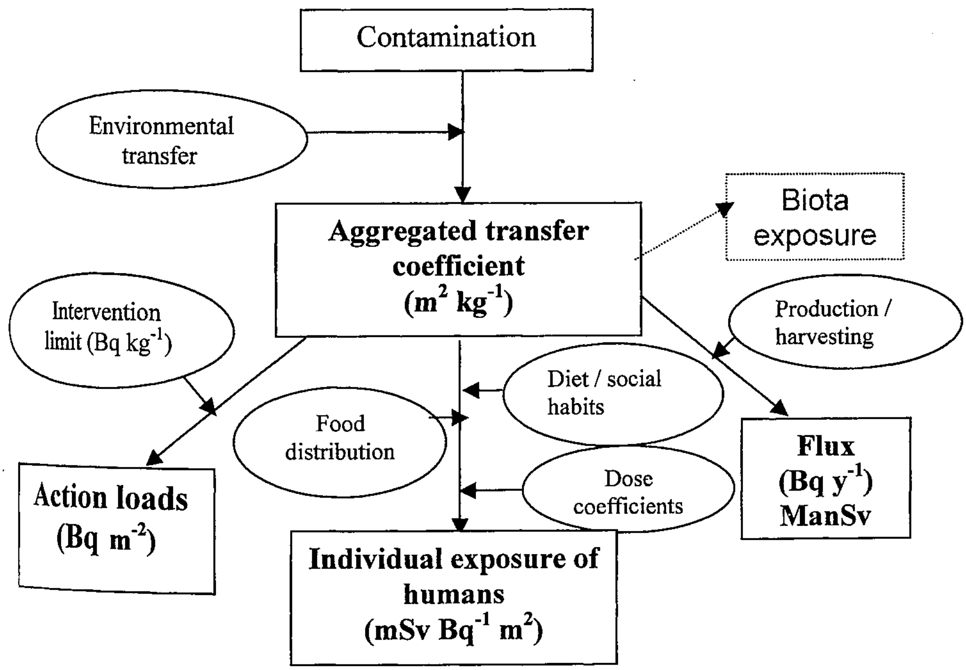


Figure 1 Scheme showing derivation and relationship between the four radioecological sensitivity indicators. All outputs are temporally and spatially variable.

### 3.1 Aggregated transfer

The aggregated transfer coefficient (Tag) is defined as the activity concentration into an environmental compartment (often a food product) (Bq $kg^{-1}$) divided by the corresponding radionuclide deposition (Bq $m^{-2}$); with units of $m^2$ $kg^{-1}$. Tag values have been most commonly used in the former Soviet Union to quantify transfer to food products. In other countries, they are often used for semi-natural products. In addition to being a useful indicator in itself for estimation of transfer to human food products, this indicator would also be relevant to sensitivity analysis of biota. High Tag values, such as those derived for highly organic soils for radiocaesium, indicate radioecologically sensitive areas. Obviously, Tag values are time dependent, and can be combined with ecological half-lives to quantify changes with time.

### 3.2 Action loads

From a radioecological perspective, the critical load for a food product has previously been defined as the level of radionuclide deposition (Bq $m^{-2}$) which leads to activity concentrations in a food product above intervention limits [4]. It is a potentially useful approach for identifying radioecologically sensitive areas for emergency planning and has the advantage of simplicity and ability to be readily presented spatially. Previously, the use of critical loads was developed for the mid-long term phase. We decided that a similar approach would be particularly useful for the acute phase after an accident. For this application, critical loads were renamed as action load. Action loads depend on processes which are important in the initial stages of an accident, such as interception and weathering. For radiocaesium, maps (or tables) of action loads for different food products can be combined with maps of deposition following any future nuclear accidents for the rapid identification of areas that are either sensitive or resilient after deposition, thereby enabling improved targeting of resources.

### 3.3 Fluxes

The flux is defined as the total amount of radioactivity produced in a specified environmental product over a given time period (eg. Bq/y) which is transferred from one compartment to another. For collective dose estimation, agricultural production statistics need to be incorporated so that fluxes of radionuclides can be quantified. To improve the quantification of the collective doses, it is important to assess the spatial dimension of the key parameters defining radioecological sensitivity.

### 3.4 Exposure to humans

According to Figure 1, one sensitivity indicator is the effective dose, normalized to 1 Bq $m^{-2}$, that an individual receives over a period of time after contamination. This dose depends both on the isotope that causes the exposure and the age of the individual exposed. Key factors affecting individual dose are where the food comes from and the dietary habits. The concept of identifying critical groups with respect to one or a few food products, and considering their sensitivity to key parameters has been well developed [5]. In addition, (radiocaesium) exposure can be enhanced by the inclusion of semi-natural products in the diet, thus, in addition to children, fishermen, hunters and consumers of forests products are radioecologically sensitive groups. In general, self-sufficiency with respect to diet and food production tends to increase radioecological sensitivity.

## 4. ECOSYSTEM SENSITIVITY

The concepts and indicators outlined above are chosen so that they can be applied to terrestrial, freshwater and marine ecosystems. For each category, modifying factors such as the lateral redistribution of contamination, application of countermeasures and interaction with other pollutants may all affect the sensitivity of end points. For instance, areas or ecosystems where it is particularly difficult to implement effective countermeasures may be considered to be radioecologically sensitive. A key factor for all ecosystems will be the bioavailability of the contaminant radionuclide. Environmentally mobile forms of radionuclides will transfer to a greater extent than those which are immobile, such as radionuclides strongly attached to particles. Some of the main considerations in each category of ecosystem are outlined below:

### 4.1 Terrestrial ecosystems

Considering only atmospheric deposition, environmental radionuclide transfer in terrestrial ecosystems can be sub-divided into three categories:

#### *4.1.1. Surface contamination*

The extent of interception by vegetation surfaces is greatly dependent upon vegetation density (season), leaf area index and plant surface characteristics, but also on dry or wet deposition. Subsequent weathering of radioactive contamination from plant surfaces will depend not only on meteorological conditions but also on plant surface characteristics. High interception by plants and long weathering rates may make an ecosystem radioecologically sensitive (e.g. coniferous forest).

#### *4.1.2. Transfer to plants*

The rate of foliar absorption is affected by the chemical form and solubility of the deposited radionuclide. Subsequent translocation will also depend on the amount intercepted and its chemical form. Radionuclide uptake by plants via roots occurs via the soil solution. The processes controlling radionuclide transfer between various soil components and the soil solution are critical for radionuclide bioavailability. For example, fixation of many radionuclides on non-specific cationic exchangeable sites is weaker than on more specific sites such as clay minerals. In addition, soil solution composition is important because of the competition between radionuclides and their stable analogues e.g. strontium and calcium, caesium and potassium. Therefore, soils with low potassium and clay mineral contents will be more radioecologically sensitive to radiocaesium than soils with high potassium and clay mineral contents. Strong fixation will enhance retention of radionuclides in upper soil layers. However, other factors will also influence soil migration such as microbial/biological activity and infiltration capacity of the soils. In general, high soil migration rates of radionuclides will reduce the radioecological sensitivity since many plants have their rooting systems located in the upper layers of the soil. However, for deeper-rooting species the reverse will apply for a certain period of time. The degree of resuspension of soil and its subsequent adhesion to plant surfaces may also be a relatively important factor in plant contamination, especially for relatively immobile radionuclides such as the actinides.

#### *4.1.3. Transfer to animals*

Transfer to animals varies with species and maintenance habits; generally smaller ruminants with higher transfer to tissues being more radioecologically sensitive than larger ruminants. Rates of gut absorption vary between radionuclides from <1% for plutonium to 100% for radioiodine, and 80-100% for plant incorporated radiocaesium, and 10-30% for radiostrontium and depends on the bioavailability of radionuclides with feed. These later three mobile radionuclides are key contaminants of milk (and meat for Cs). Tissue distribution and retention varies and radioecological sensitivity depends on the extent of transfer to target tissues (commonly quantified using the transfer coefficient) and biological half-lives. Diet selection by animals is variable, especially in ecosystems with high vegetation species diversity. For example, mushroom ingestion by roe deer in the autumn, of lichen in winter by reindeer and of heather by grouse causes high seasonal contamination of their meat.

### 4.2 Freshwater ecosystems

Estimates of the initial activity concentration in water bodies can be made by assuming dilution of activity directly deposited onto the river or lake surface, and therefore deep rivers and lakes would be expected to be initially less sensitive than shallow ones. However, deposition times can be long compared to river water transit times, and catchment runoff makes a significant contribution to water activity concentrations. Activity concentrations of radionuclides in runoff water declines significantly over time after fallout. At a given point in time, the activity concentration in river water per unit of deposition to the catchment (the *runoff coefficient*) is a measure of radioecological sensitivity of the catchment. Long-term runoff coefficients of Cs and Sr have been well quantified, and are predictable, using soil characteristics. For example, organic, boggy catchments have much higher $^{137}Cs$ runoff coefficients than catchments with high coverage of mineral soils [6].

Removal of the initial deposit of radioactivity from lake and reservoir water may be estimated using the water residence time in lakes and simple models for removal of radioactivity to sediments. Long term activity concentrations in lakes with relatively short water residence times are primarily controlled by inputs of radioactivity from the surrounding catchment. Long term activity concentrations in closed lakes, where there is relatively low turnover of water, is controlled by transfers of radioactivity to and from bottom sediment deposits. Thus, for radiocaesium, lakes of high radiosensitivity are shallow lakes of low water turnover rate, and those lakes in catchments with a high percentage of organic boggy soils.

All other things being equal, the radiocaesium activity concentration in fish is inversely proportional to the potassium concentration of the surrounding water [eg. 7]. High potassium concentrations in water are often a result of runoff of agricultural fertilisers, so fish in water bodies in intensive agricultural areas are likely to be less sensitive to $^{137}Cs$ uptake than those in natural or semi-natural areas. Similarly, an inverse relationship has been determined between $^{90}Sr$ activity concentrations in fish and water calcium concentration [e.g 7]. Transfer rates to fish also depend on feeding strategies, with caesium activity concentrations in the more radioecologically sensitive predatory fish being a factor of two or more higher than non-predatory.

### 4.3 Marine ecosystems

Marine ecosystems are relatively insensitive compared to the freshwater and terrestrial environments. Such insensitivity is a result of the capacity of marine ecosystems to quickly dilute an input of radioactive pollutant as a consequence of processes such as advective currents and waves, coupled with the large volumes involved. Thus, short term consequences are likely to be more important in marine ecosystems as dilution will occur over the long term.

Radioecological sensitivity in marine ecosystem will be affected by these key factors: (i) sedimentation rates (ii) concentration factors of different marine species (phytoplankton, zooplankton, crustacea, molluscs and fishes) (iii) residence times of radionuclides in the water column (iv) suspended load concentrations (v) sediment distribution coefficients (kds) (vi) bioturbation coefficient (vii) chemical forms of radionuclides (viii) marine currents and (ix) velocity of interchange with estuarine freshwater.

Furthermore, sensitive marine ecosystems will include those into which liquid discharges are released (eg Irish sea affected by Sellafield Reprocessing Plant activities, coastal areas close to the influence zones of La Hague and Marcoule, emissions of natural radioactivity of non-nuclear industries, areas affected by accidents). In addition, estuarine areas used extensively for farming molluscs (eg Galicia produces 90% of Spanish molluscs and production is high in some French Atlantic coasts), fish (eg Nordic estuarine areas) and crustaceans and also marine zones of high biological productivity such as the Barents sea may be considered as radioecologically sensitive.

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