RADIOECOLOGICAL SENSITIVITY CONCEPT DOCUMENT
11 February 2010

Purpose

This document was prepared by EMRAS-II, Working Group 8 on Environmental Sensitivity. It was drafted, not as a final report, but as an interim document, to provide guidance to the working group on the design of scenarios and the carrying out of exercises on environmental sensitivity.

What is meant by environmental or radioecological sensitivity?

Environmental sensitivity, broadly speaking, can be defined as the “relation between the response of a particular environment unit to a given stress, and the severity of that stress” (Buckley,1982). It provides an “environmental state of reference that can be readily used for contingency planning and can be regularly updated as new elements or changes come into play” (Populus et al, 1995).

The stress-response relation may take different forms (Buckley, 1982), depending on, for example, the reversibility of the environmental response, the critical load of the system affected, the time factor and the interdependence between various environmental components. When the stress factor involved is radioactive pollution, it becomes a matter of identifying the exposure routes, the exposed individuals, and the geographical areas of most concern (Howard, 2000).

One and the same load (fallout or discharge) of a radionuclide entering a given ecosystem may give rise to very different activity concentrations in soil, water and biota. This will also lead to a large variability in the dose to both humans and non-human biota. The origin of these differences lies in four main factors (Howard, 2000):

- pathways having higher or lower transfer for particular radionuclides;
- different lifestyle habits (e.g diet);
- location (e.g. proximity to a nuclear installation);
- habitats and communities (e.g. ecosystem responses to contamination or to countermeasures that have been implemented).

Spatial variation and radionuclide specificity are inherent characteristics of environmental sensitivity. As an example, lakes low in potassium will be sensitive to radiocaesium fallout as the biota will, in the absence of potassium, scavenge its analogue caesium, leading to higher activity concentrations in fish. In such lakes addition of potash is one obvious method to reduce the potential dose to humans and non-human biota.

An additional facet of radioecological sensitivity involves the feasibility and effectiveness of various countermeasures in reducing radiation doses to humans and non-human biota. Depending on, for instance, soil type or agricultural production characteristics, the same countermeasure may be more or less effective and may cause environmental side effects.

In the simplest case, the concept of radioecological sensitivity can be applied to one particular environment with no reference to other environments. Prior identification of sensitive areas – for instance in the perimeter around nuclear installations- and critical population groups can be a useful input into emergency planning and preparedness (Howard 2000; Mercat-Rommens and Renaud 2004).

Alternatively, radioecological sensitivity analysis can be used as an aid to decision making, since it allows comparison and prioritisation of different environmental compartments and zones affected by radioactive contamination. In particular, radioecological sensitivity mapping provides a strategic and objective overview of potentially affected territory, helping to indentify areas which may be particularly sensitive. This method has found a number of applications in land-use planning and disaster management. In recent years, sensitivity mapping combined with multi-criteria decision-aid techniques, has been proposed in the context of radioecological sensitivity as an aid in risk management and decision-making (Mercat-Rommens and Renaud, 2004).

In the above analysis, the environments compared could belong either to the same category (e.g. agricultural environment in different countries or with different crops and animal products) or to different categories (e.g., agricultural, forest, alpine, or arctic environments).

A mathematical definition of environmental sensitivity

Model sensitivity analysis concerns models rather than empirical facts. Environmental sensitivity is, on the contrary, an empirical fact. Therefore, to give an "operational" definition of Environmental Sensitivity is to prescribe the procedures required to determine or measure it. When direct measurements of the stress-effect relation are not available, models can be used *to predict* the environmental sensitivity of a given ecosystem.

From the restricted definition (Håkanson et al., 1996) "A given load (=fallout) of any substance to a given lake may cause very different concentrations in water and biota depending on the characteristics of the lake and its catchment" we can derive a general definition of Environmental Sensitivity (ES) as the ratio between a measure of an environmental effect (E) and a measure of an external stimulus (or threat) (S):

$$\mathrm{ES} = \frac{\text{Measure of an environmental effect (E)}}{\text{Measure of an external stimulus (S)}} = \mathrm{E/S} \; \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

To illustrate this definition, consider the accidental release of radionuclides into a lake. The measure of external stimulus can be the "pulse" deposition per unit surface D (Bq m-^{2}) of radionuclide on the lake. One or more environmental sensitivity factors can be selected, for instance, on the basis of their importance to human health. A good example could be the radionuclide concentration in a fish species largely consumed by humans. Since the concentration in fish depends on time, the measure of the effect could be the integrated time concentration from the instant that the accidental deposition occurred.

$$\text{Measure of the effect} = \int_0^\infty \mathrm{C(t)dt} \qquad (2)$$

$$\mathrm{ES} = \frac{\int_0^\infty \mathrm{C(t)dt}}{\mathrm{D}} \qquad (3)$$

The definition can be easily extended to other factors. C(t) could represent the radionuclide concentration in lake water. In the case of terrestrial ecosystems, C(t) could be the concentration in vegetation, in living species, or in any other biotic or abiotic component. ES can depend on the time the contaminant is introduced into the environment (seasonal effects). The most obvious example is the contamination of vegetation: the effects are very different if the deposition occurs during the "dormancy" season or during the "active" season. Similarly, the effect on water contamination can be different if deposition occurs on the ice covering a lake or directly on water.

Note that ES depends on the characteristics of contaminant release. Equation (3) refers to a single pulse input. In the case of a chronic release ES would depend on the duration of the contaminant input. Moreover the effects can be different if the release occurs in different environmental compartments.

The above definition of environmental sensitivity requires the identification of the “measure of the external stimulus”. Should it be the total amount of radionuclide introduced into the system or should it be a derived quantity such as the deposition per square metre? Different definitions of external stimulus imply differing evaluations of the sensitivity of a specific environmental system. For example, in the case of lakes, the sensitivity derived from deposition per unit area can be quite different from that derived from total radionuclide to the lake, since the latter depends on the area of the lake.

The notion of environmental sensitivity can be extended to the assessment of the overall impact of any event of environmental contamination. This assessment is commonly based on the three canonical elements of evaluation: the environmental, the social and the economic impacts. The policy of the regulator or governing body is of importance in choosing environmental sensitivity factors. For instance, the factors can be the concentrations of radionuclides in different environmental components, the doses to biota, or further suitable ecological indices in view of the importance attributed to the direct impact on human health or on the ecosystem and of the evaluation of the effectiveness of countermeasure strategies for reducing these impacts.

Definition (1) is useful when effect is proportional to stimulus. The main advantage of this definition is the possibility of comparing the Environmental Sensitivity of different systems. When the effect is not proportional to the stimulus, the definition of Differential Environmental Sensitivity (DES) can be useful:

$$\mathrm{DES} = \frac{\partial \mathrm{E}}{\partial \mathrm{S}} \qquad (4)$$

Model sensitivity and uncertainly analysis

In assessing the radioecological sensitivity and the related variability of radiation doses, model sensitivity and uncertainty analysis are commonly employed (Howard, 2000).

Sensitivity analysis ascertains which environmental parameters are most “responsible” for ecosystem sensitivity and can thus lead to higher doses. This requires that the model includes the particular parameter or set of parameters as input variables, although there may be proxy variables that estimate the sensitive parameter. Sensitivity analysis helps ranking the input parameters based upon how much impact they have on the output end point.

Uncertainty analysis provides an indication of where the greatest uncertainty lies in the model and which parameter estimates need to be improved in order to achieve better predictions. This involves a determination of the variations in the output results based upon variations in input parameters. Usually, the uncertainty analysis is done prior to the sensitivity analysis.

The following example will illustrate these processes more clearly. Suppose we have a model for calculating ingestion dose to an adult from an airborne release of Cs-137 with the following 14 input parameters:

- Wind speed
- Stability class
- Roughness length
- Transfer rate from air to leafy vegetables (nuclide specific)
- Transfer rate from air to non-leafy vegetables (nuclide specific)
- Transfer rate from air to forage (nuclide specific)
- Dairy cow's intake rate of forage
- Beef cattle's intake rate of forage
- Transfer rate from forage to cow's milk (nuclide specific)
- Transfer rate from forage to beef (nuclide specific)
- Adult consumption of leafy vegetables
- Adult consumption of non-leafy vegetables
- Adult consumption of milk
- Adult consumption of beef

Uncertainty analysis: We first define a probability density function (PDF) for each of the input parameters. A random number generator is used to pick 100 samples from each of the PDFs. The model is run, say 100 times, starting with a hypothetical release rate and calculating the dose according to the 100 sampled input parameter values. Out of the 100 dose results, suppose the following results are obtained:

- minimum dose = 5 µSv
- 2.5 percentile dose = 7 µSv
- mean dose = 55 µSv
- 97.5 percentile dose = 83 µSv
- maximum dose = 90 µSv.

In this uncertainty analysis, there is a 95 % probability that the dose to an adult will lie between 7 and 83 µSv.

Sensitivity analysis: Using a random number generator, we create 14 tables, one for each input variable, and each containing 100 sampled values. Then, by running the model, we create one output table containing 100 resulting values. Now, we calculate the correlation coefficients between the output end points and the values of each input parameter. Thus we determine which parameters are most closely related (directly or inversely) to the doses. Suppose the stability class came as the top parameter with a correlation coefficient of 0.97, with stability class A giving 5 µSv and stability class F, 90 µSv. Thus stability class ranks #1 in sensitivity. Similarly, if some other parameter (e.g. transfer factor to leafy vegetables) gives a correlation coefficient of 0.90 it would be ranked #2. This process of ranking the input parameters by their correlation coefficients continues for all of the parameters.

Scenario development

1. Environments to be modelled.
    - Agricultural
    - Temperate forest
    - Alpine
    - Arctic

There may be some overlap between these environments, but for now we will treat them separately.

2. The radionuclide inputs to the ecosystems. The starting point for all environments should be a deposition per unit area for each of several key radionuclides. The list of radionuclides should be a reasonable representation of what might be expected in a release from a serious

nuclear accident such as Chernobyl.. The following table, adapted from IAEA (1991) may prove helpful here.

Radionuclide	Half-life	Inventory (PBq)	% released	Release (PBq))
I-131	8.05 d	1300	20%	260
Te-132	3.25 d	320	15%	48
Cs-134	2.06 y	190	10%	19
Cs-137	30.17 y	290	13%	37.7
Mo-99	2.8 d	4800	2%	110.4
Zr-95	64.0 d	4400	3%	140.8
Ru-103	39.5 d	4100	3%	118.9
Ru-106	368 d	2000	3%	58
Ba-140	12.8 d	2900	6%	162.4
Ce-141	32.5 d	4400	3%	123.2
Ce-144	284 d	3200	3%	89.6
Sr-89	53 d	2000	4%	80
Sr-90	29 y	200	4%	8
Pu-239	24,110 y	0.85	3%	0.0255
Pu-240	6537 y	1.2	3%	0.036
Pu-241	14.7 y	170	3%	5.1

Of course, we don't need to consider all these radionuclides, and there may be others we wish to add. The goal is to have a reasonable variety of radionuclides, because different radionuclides may behave very differently in different ecosystems, and we want to model this variability. We can use field measurement data after the Chernobyl accident to derive some reasonable depositions in Bq/m^2.

3. Timeframe. The deposition event is short-term since we are modelling accident situations. The event should be repeated at least four times per year, in order to model seasonal effects. Also, the effects should be modelled over different periods of time – days, weeks, months, years. We know that some of the environmental impacts of Chernobyl continued for years, even decades.

4. Environmental compartments . At very least, we need to consider the abiotic compartments of soil, surface water bodies, sediments (?) and possibly resuspended soil particles (airborne pathway). The choice of plants and animals will depend on which ecosystem is being modelled. A key factor will be the consideration of food chains leading to human consumption. This will require further discussion as the specifics of each environment are developed.

5. Endpoints. The endpoints could be radionuclide concentrations in key abiotic and biotic compartments. They could also be radiation doses to humans and non-human biota. This needs further elaboration.

6. Uncertainty and sensitivity analyses. If the models contain probability density functions (pdfs), then modellers should be encouraged to report uncertainty estimates on their predictions. Sensitivity analyses will be particularly valuable for this Working Group, as we hope to learn which radionuclides and which pathways are most critical for each of the ecosystems.

7. Effectiveness of countermeasures. What countermeasures should be considered and how do we gauge their effectiveness?

References:

Buckley, R.C. (1982). Environmental sensitivity mapping: what, why and how? *Earth and Environmental Science* 4(4): 151-155.

Håkanson, L., Brittain, J. E., Monte, L., Bergström, U. Heling, R., 1996. Modelling of radiocesium in lakes – Lake sensitivity and remedial strategies. Journal of Environmental Radioactivity 33, 1-25.

Howard, B. (2000). The concept of radioecological sensitivity. *Radiation Protection Dosimetry* 92(1-3): 29-34.

Mercat-Rommens, C. and Renaud, P. (2004). How can we use the radioecological sensitivity asa tool for risk management. *EUROSAFE Forum, 8-9 November 2004*, Berlin. Available online at http://www.eurosafe-forum.org/files/pe_99_24_1_3_06_radioecolog_sensivity_031104.pdf

Populus, J., Moreau, F., Coquelet, D., Xavier, J.-P. (1995). An assessment of environmental sensitivity to marine pollutions: solutions with remote sensing and Geographical Information Systems (GIS), *International Journal of Remote Sensing*, http://www.informaworld.com/smpp/363953712-3732212/title~db=all~content=t713722504~tab=issueslist~branches=16 - v1616(1): 3 – 15.

IAEA (1991). The International Chernobyl Project – Technical Report. Report by an International Advisory Committee. International Atomic Energy Agency, Vienna., p. 69.