A probabilistic approach to environmental impact assessment of a radioactive contamination

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Abstract. Since a radiological environmental impact assessment typically relies on limited data and poorly based extrapolation methods, point estimations, as implied by a deterministic approach, do not suffice. To be of practical use for risk management, it is necessary to quantify the uncertainty margins of the estimates as well. In this paper we discuss how to work out a probabilistic approach for dealing with uncertainties in assessments of the radiological risks to non-human biota of a radioactive contamination. Possible strategies for deriving the relevant probability distribution functions from available empirical data and theoretical knowledge are outlined.

1. INTRODUCTION

A system that considers explicitly radiological risks to non-human biota is needed; on this it seems to be consensus. Due to the very high environmental variability innumerable combinations of types of biota and habitats need to be considered. Several simplifications for dealing with the environmental variability have been proposed [1], basically by focusing risk assessments on the most exposed, radiosensitive and ecologically significant organisms (reference organisms). The basic notion is that if the reference organisms were protected, then other organisms are also protected.

Due to lack of knowledge about effects of low radiation doses on living organisms and about the environmental behavior of radionuclides it is necessary to deal with very large uncertainties. An approach frequently used to sort out the uncertainties (here called the deterministic approach) is to compare the exposure against a single conservative reference value. The main advantage of this approach is its simplicity, which facilitates carrying out screenings with a minimum of information. However, problems arise when the conservative reference values are actually exceeded or might be exceeded, as in the case of potential exposures, and when the costs for realizing the reference values are high. In those cases the lack of knowledge on the degree of conservatism involved impairs a rational weighing of possible radiological risk to biota against other interests. Furthermore, due to the biodiversity and variability of exposure pathways and radiation effects, it might be impractical to use a single conservative reference value for risk characterization.

Since a radiological risk assessment typically relies on limited data and poorly based extrapolation methods, point estimations, as implied by a deterministic approach, do not suffice. To be of practical use for risk management, it is necessary to quantify the uncertainty margins of the estimates as well. Hence, in the definition of standards for risk estimation, the quantification of the uncertainties involved is essential, and a probabilistic approach is the natural way of dealing with it. In this paper we discuss how to work out a probabilistic approach for assessing the radiological impact of a radioactive contamination of the environment on the non-human biota. Our first aim is to delineate the probabilistic approach in comparison with the deterministic approach and to define the entities involved and their relationship. The second aim is to identify possible strategies for deriving the relevant probability distribution functions from available empirical data and theoretical knowledge.

2. DETERMINISTIC APPROACH

The central concept of the deterministic approach is to characterize the risk to biota as a quotient (RQ) of the estimated exposure value (EEV) and a reference value (RV), where value is dose rate to the biota or concentration in the environment (soil, water, sediments, air, etc).

$$RQ = \frac{EEV}{RV} \tag{1}$$

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Values of the dose rate or environmental concentrations below which it is unlikely to observe adverse effects in the biota are used as RV. If the calculated risk quotient (RQ) is less than unity, then there is some assurance that the risk is low. If very conservative values are used for the EEV and RV, then there is high assurance that the risk is low, i.e. the probability of the toxic effect is very low.

If concentrations are used in equation (1), then the RV (here called RV(C)) can be derived from the RV expressed in terms of dose (here called RV(D)) by the following general expression:

$$RV(C) = \frac{RV(D)}{BF \cdot DCF_{in} + DCF_{ex}} \quad (2)$$

Where,

RV(C) is the reference value expressed in terms of concentrations in a specific environmental medium,
RV(D) is the is the reference value expressed in terms of dose rates to the reference organism,
BF is a bioaccumulation factor expressing the relationship between the concentrations of the radionuclide in the environmental medium and the concentration of the radionuclide in the reference organism,
DCF_{in} is a dose conversion factor expressing the relationship between the radionuclide concentration in the reference organism and the internal dose rate to the organism,
DCF_{ex} is a dose conversion factor expressing the relationship between the radionuclide concentration in reference media and the external dose rate to the reference organism.

In the deterministic approach, normally, conservative values are used for the factors in equation (2). Given the multiplicative nature of the model a substantial magnification of the conservatism may occur. As a consequence, values of RQ close to or above 1 will not carry any information about actual risks. A common way to deal with this problem is to carry out assessments in tiers. This means that if a conservative assessment yielded RQ > 1, then more detailed, realistic quotients will be estimated. This approach could be seen as a simplified version of a probabilistic approach. In any case the interpretation of the results would require knowledge about the distribution of EEV and RV. For example, using mean values in equation (1) is meaningful if EEV and RV follow a normal distribution, which is rarely the case.

3. PROBABILISTIC APPROACH

In the probabilistic approach the EEV and the RV are considered as random variables with probability density functions *f (l) and f(s)* respectively. Hence, the RQ should also be considered as a random variable. The deterministic RQ calculated with equation (1) can be seen as single point estimates belonging to the universe of all possible RQ values.

The probability (R) that RQ exceeds unity equals the probability of the relevant toxic effects, i.e. the risk, and it can be estimated with the equation (3):

$$R = P\left(\frac{EEV}{RV} > 1\right) = \int_0^{\infty}\left(\int_0^{l} f(l,s)ds\right)dl \quad (3)$$

Where,

$f(l,s)$ is the joint probability density function of the random variables EEV and RV.

In the case when the EEV and RV in equation (3) are expressed in terms of concentrations, the probability density function of the RV(C) can be estimated by the following procedure: i) the values of RV(D), BF, DCF_{in} and DCF_{ex} in equation (2) are substituted with the corresponding probability density functions, ii) by means of Monte Carlo simulations an array of values of RV(C) is generated, iii) these values are processed statistically to derive the probability density functions of RV(C).

The probability distributions of BF, DCF_{in} and DCF_{ex} are needed even when the EEV and RV are expressed in terms of dose rate. In this case they are used for estimating the EEV in terms of dose rate from calculated or measured radionuclides concentrations in the environment.

The acceptance of the probabilistic approach hinges on sufficient support from data and knowledge to obtain the necessary probability distributions. A discussion on possible strategies for deriving the probability density functions of RV(D), BF, DCF_{in} and DCF_{ex} as well as the probability distributions for the radiobiological effectiveness (RBE) of high-LET radiations follows below.

The probabilistic approach could, in principle, be implemented gradually. This means, that probability distributions could be incorporated in the RQ as they become available and could be successively improved by incorporating new information and knowledge. The probabilistic approach is more robust than the deterministic in the sense that new information and knowledge would lead to less dramatic changes in probabilistic risk estimations. Another advantage of the probabilistic approach is that it permits deriving screening values of RQ with the desired level of conservatism.

4. DOSE REFERENCE VALUES

Laboratory and field experimental data on the effects of exposure to radiation have been reviewed by several international agencies with the purpose of identifying radiation dose rates below which effects on populations of organisms would not likely occur [2, 3, 4]. This information has been used to derive radiological protection standards in terms of dose rates to biota that would ensure protection of the populations. The standards have been usually expressed in terms of single dose rate values for terrestrial plants, terrestrial animals, aquatic organisms, etc.

The above standards are to some extent equivalent to the Critical Toxicity Values (CTV) widely used in ecotoxicology. The CTV is an estimate of the low toxicity effects in a population and is the numerical value at which small fraction of an exposed population is expected to be affected [5]. The values that are usually used as RV for estimation of the RQ are the so-called Estimated Non-Effect Values (ENEV). The ENEV is defined as the level at which no biological or ecological effects are expected to be observed in the receiving population. The ENEV is calculated from the CTV using application factors based on the quality of the data used to obtain the CTV and to take into account the interspecies extrapolation and extrapolation from laboratory to field. The application factors are usually in the range from 10 to 1000.

The wide range (various orders of magnitude) of doses and dose rates reported to cause effects in non-human species makes the recommendation of a single numeric value of the CTV difficult. This supports the consideration of the CTV as random variables as it is implicit in the probabilistic approach. Empirical probability distributions for different effects and types of organisms may be obtained by statistically processing existing experimental data, which is rather extensive. Subjective probability distributions could also be obtained through elicitation of experts in the field. This would be especially useful when sufficient experimental data for deriving empirical distributions is not available.

Attempts to use probability distributions as an alternative to application factors between the CTV and the ENEV have been reported for other types of contaminants [6,7]. To obtain these distributions ratios between observed CTV were computed and statistically analysed. Another possible approach is to develop "default" probability distributions for the application factors, which can progressively be improved as new information becomes available. The procedure consists of postulating a certain distribution type, commonly lognormal distributions, and assuming that a certain application factor correspond to a certain percentile of the distribution, i.e. the 99^{th} percentile [6]. Often it can also be assumed that the application factors cannot be less than 1 and hence unity could be considered as the lower bound of the distribution. Similar procedures can also be used for obtaining ENEV for radionuclides.

The background radiation is another possible point of reference for estimating the probability of adverse effects is. If we postulate that any dose above normal background doses may lead to additional unspecified adverse effects, then the probability of the effects could be estimated with the equation (3). The difference between the background dose rates (B) and a predefined background level, considered as a normal background dose rate (NB), would serve as RV(D). Since the background dose rate (B) is a

random variables, the RV(D) = B-NB will also be a random variable. The value corresponding to a chosen percentile of the distribution of background dose rates could be used as NB. Multiples of (B-NB) could also be used as RV(D) in equation (3). This way the gap between the background dose rates and the ENEV could be filled.

5. RADIOBIOLOGICAL EFFECTIVENESS

The RV(D) are usually expressed in terms of *absorbed* dose rates and have been mainly derived from studies of radiation effects to biota resulting from exposures to photons having a low linear energy transfer (LET). For exposure of biota to alpha particles, i.e. high-LET radiation, these values are usually increased by a factor representing the relative biological effectiveness (RBE) of this type of radiation as compared with the low-LET radiation.

The probability distributions of the RBE could be obtained by statistically processing available experimental data. Given the wide range of RBE reported in the literature (<1 to 300) it might be necessary to derive several probability distributions depending on the type of exposure (chronic or acute). Most likely combining empirical and subjective probabilities will be necessary.

The probability distributions of the RBE could also be estimated by generating a vector of quotients of the values of the linear energy transfer (LET) in water for α particles with energy up to 10 MeV, and the LET values for electrons with energies in the range of 0.01 to 2 MeV. A deterministic variant of this method using minimum and maxim values of the LET in order to estimate extreme values of the RBE is outlined in [2].

6. BIOACCUMULATION FACTORS

Probability distributions of bioaccumulation factors can be obtained from radioecological empirical data, currently extensively available for many radionuclides and environmental components. This could be easily made by combining probability distributions by means of Monte Carlo simulations. In many cases well-known simple distributions are available and therefore they could be combined by simple analytical procedures. When experimental data are not available for a given radionuclide, sometimes the bioaccumulation factors can be estimated from data available for their chemical analogous.

Empirical bioaccumulation factors are usually calculated from measured data under the assumption of equilibrium. Another implicit assumption is a linear relationship between the concentrations in different media. For example, the widely used soil-to-plant concentration ratio (CR) presumes a linear relationship between the radionuclide concentration in soil and the plant with a zero intercept. This has been discussed extensively in the literature, and it can be shown that linearity is not always the case [8,9] and may only rarely be the case. To conserve simplicity the deviation from linearity is considered a component of the variation in CR. In this sense using probability distributions is more consistent than using single conservative values.

Probability distributions of bioaccumulation factors can also be obtained by making probabilistic simulations with radioecological models of the radionuclide migration in the environment. Radioecological models of various ecosystems are available for some radionuclides, which could also be adapted for other radionuclides. This approach was applied in [10] to estimate bioaccumulation factors to riparian and terrestrial animal receptors using kinetic / allometric models.

7. DOSE CONVERSION FACTORS

Due to the large heterogeneity and variability of the environment, it seems overoptimistic to expect that realistic dose estimations can be made using a single value of the DCF. The approach that has prevailed so far is to estimate dose conversion factors using dosimetric models simplified through very conservative assumptions [10,11]. The degree of conservatism of the assumptions made is, however, unknown.

As pointed out by Pentreath and Woodhead [1], physical descriptions of the processes by which energy is transferred from α and β particles, and from γ and X- rays, have already been developed theoretically from first principles, and these have been expressed mathematically. But due to the energy-dependent and stochastic nature of the processes involved, they are not easy to apply to environmental situations. The application of these theoretical descriptions in combination with Monte Carlo simulations is a promising method for resolving the stochastic nature of the system and would allow obtaining probability distributions of the dose conversion factors. Some rationalisations are, however, almost mandatory for reducing the number of calculations needed to a reasonable amount. For example, to reduce the range of geometries considered some idealisations of geometries of organisms and the environment could be made [1]. Furthermore in many cases it would be sufficient to use simple dosimetric models in the simulations, like those outlined in [12].

8. CONCLUSIONS

A probabilistic approach is a natural way of dealing with uncertainties in estimations of risks to biota from exposure to ionising radiation. This method is more flexible, robust and informative than the more commonly used conservative deterministic approach. The advantages of the probabilistic approach become more evident when the risks are not trivial. The general acceptance of this approach hinges on sufficient support from data and knowledge to obtain the relevant probability distributions. In this paper we have shown that this is workable approach and have outlined some possible strategies to derive the required probability distributions. A gradual implementation of the probabilistic approach is possible. Probability distributions could be incorporated in the risk quotients as they become available and could successively be improved as new data and knowledge are obtained.

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