# Dose (external, internal) to biota calculation/assessment (ERICA) – PART 1

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EU COMET course:
*"COURSE ON NATURALLY OCCURRING RADIOACTIVE MATERIAL (NORM) IN THE ENVIRONMENT"*

# Environmental protection from ionising radiation in practice (the historical view)

- End of 1990s – protection of the environment based upon human radiological protection citing (ICRP-60; para 16) :
  - *"The Commission <u>believes</u> that the standard of environmental control needed to protect man to the degree currently though desirable will ensure that other species are not put at risk. Occasionally, individual members of non-human species might be harmed, but not to the extent of endangering whole species or creating imbalance between species*. *At the present time, the Commission concerns itself with mankind's environment only…."*
- Problems ?
  - Where is the evidence ? An article of faith as oppose to a scientifically supported fact.
  - What happens in situations where there is no (environmental) connection with humans ?
  - Why is radioactivity treated in a different way to other contaminants ?
  - How can we evaluate the impact from radiaoactivity within a wider, environmental managment, context (e.g. in relation to resource management, $CO_2$ emissions – climate change etc.)

# Reaction

- Several groups (IUR, USDoE, SSI, EA, NRPA) identified the need for a clear, structured framework to allow environmental impact assessments to be performed
- The EU accepted arguments from European institutes : supported the projects EPIC + FASSET (2000-2003) and thereafter ERICA (2003-2007)
- International Commission on Radiological Protection
    - Through the work of Committee 5 : began to reevaluate their position in relation to environmental protection of the enviironment and recommend a way forward.

# ICRP environmental protection

- New recommendations – ICRP(2007)
  - Planned, existing and emergency situations
  - all of the environment needs to be considered, including areas where humans are absent.
- Aims of environmental protection now include
  - Preventing or reducing the frequency of deleterious radiation effects to a level where they would have a negligible impact on the maintenance of biological diversity, the conservation of species, or the health and status of natural habitats, communities, and ecosystems.

ICRP, 2007. The 2007 Recommendations of the International Commission on Radiological Protection. ICRP Publication 103. Ann. ICRP 37(2–4).

# ERICA

Environmental Risk from Ionising Contaminants:
Assessment and Management

**EU EURATOM : Contract FI6R-CT-2003-508847**
**NFR : Contract No. 163294**

**http://www.erica-project.org/**

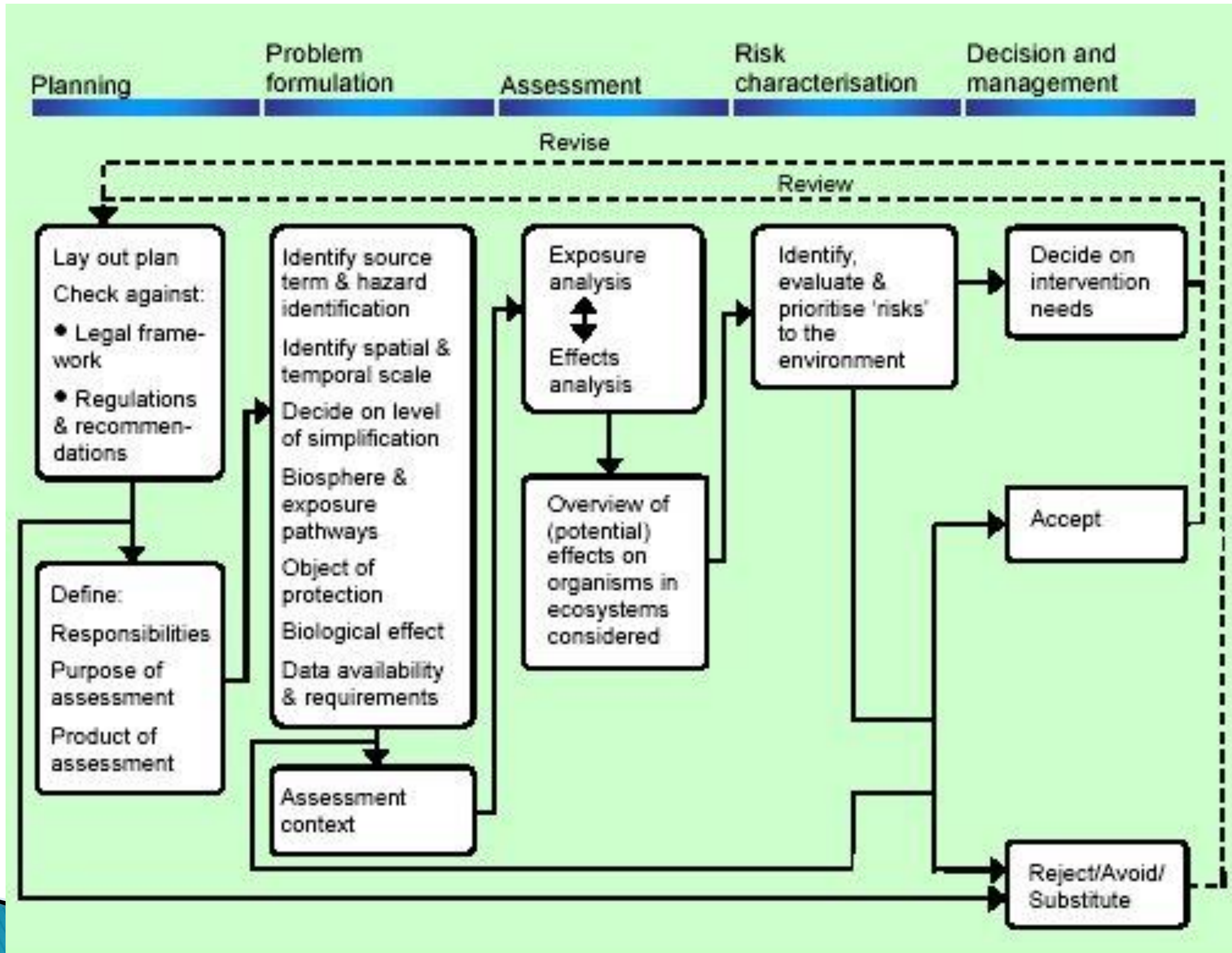
**SSI, SKB, SUC, Facilia GSF, CIEMAT, IRSN, EDF, EA, WSC, UniLiv, CEH, UMB, STUK.**

# What is the ERICA Integrated approach ?

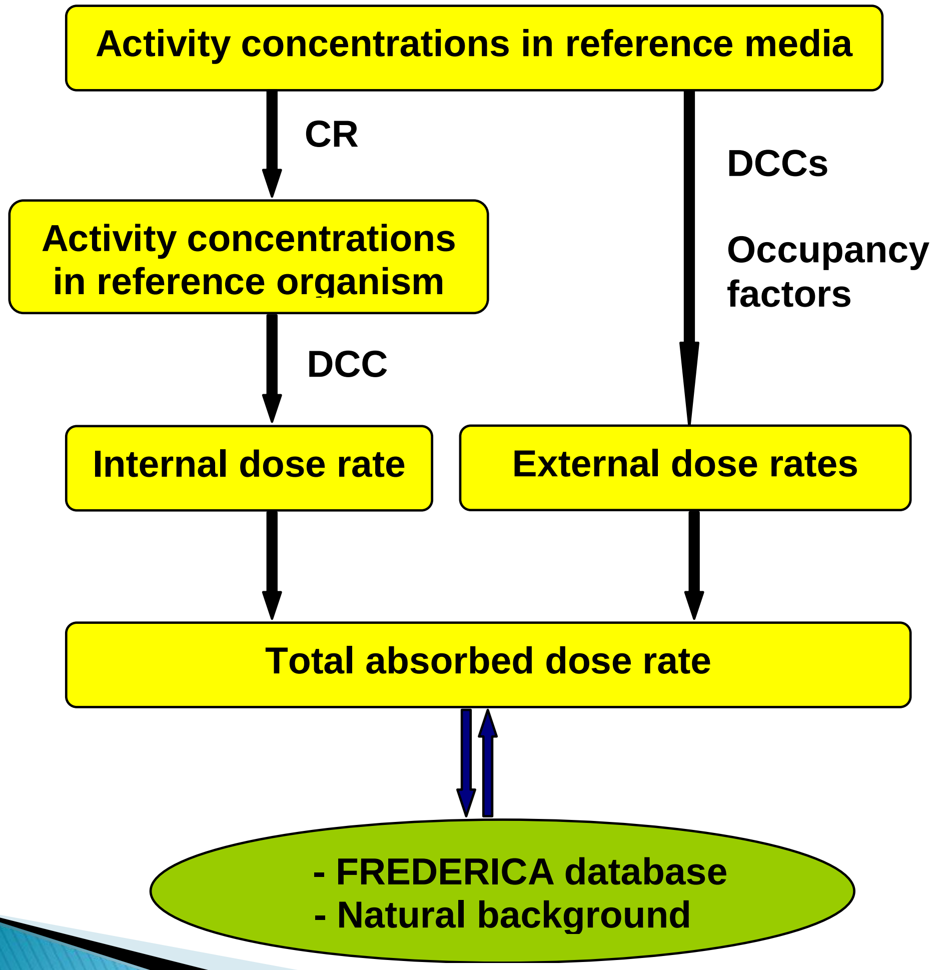
- Provides an approach for performing environmental impact assessment for radioactivity
  - giving appropriate weight to the exposure, effects and risks from ionising radiation, with emphasis on safeguarding the structure and function of ecosystems.
- To fulfil this objective, elements related to environmental management, risk characterisation and impact assessment have been integrated into what was termed the ERICA Integrated Approach.

Larsson, C. M. (2008). An overview of the ERICA Integrated Approach to the assessment and management of environmental risks from ionising contaminants. *Journal of Environmental Radioactivity, 99*, 1364–1370.

# Elements in a stepwise environmental assessment and management procedure



# Components within the assessment part




- Modelling transfer through the environment
- Estimating doses to biota from internal and external distributions of radionuclides
- Establishing the significance of the dose-rates received by organisms

# Reference organisms

- A RAP is defined as:
  - *‘ a hypothetical entity, with the assumed basic biological characteristics of a particular type of animal or plant, as described to the generality of the taxonomic level of Family, with defined anatomical, physiological and life-history properties, that can be used for the purposes of relating exposure to dose, and dose to effects, for that type of living organism.’*
- A reference organism (as used in ERICA) is defined 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*.’
- ERICA reference organism
  - Selected via various criteria : radioecological sensitivity, radiobiological sensitivity
  - Bias towards European plants and animals
  - Encompasses protected species within Europe – connection to regulations

# Examples of reference organisms

| Terrestrial | | Marine | | Freshwater | |
|---|---|---|---|---|---|
| Soil Invertebrate | Earthworm | Phytoplankton | | Phytoplankton | |
| Detritivorous invertebrate | | Macroalgae | B. seaweed | Vascular plant | |
| Flying insects | Bee | Vascular plant | | Zooplankton | |
| Gastropod | | Zooplankton | | Insect larvae | |
| Lichen & bryophytes | | Polychaete worm | | Bivalve mollusc | |
| Grasses & Herbs | Grass | Bivalve mollusc | | Gastropod | |
| Shrub | | Crustacean | Crab | Crustacean | |
| Tree | Pine | Benthic fish | Plaice | Benthic fish | |
| Mammal | Deer & Rat | Pelagic fish | | Pelagic fish | Trout |
| Bird | Duck | (Wading) bird | | Bird | Duck |
| Bird egg | | Mammal | | Mammal | |
| Reptile | | Reptile | | Amphibian | Frog |
| Amphibian | Frog | Sea anemones/true corals | | | |

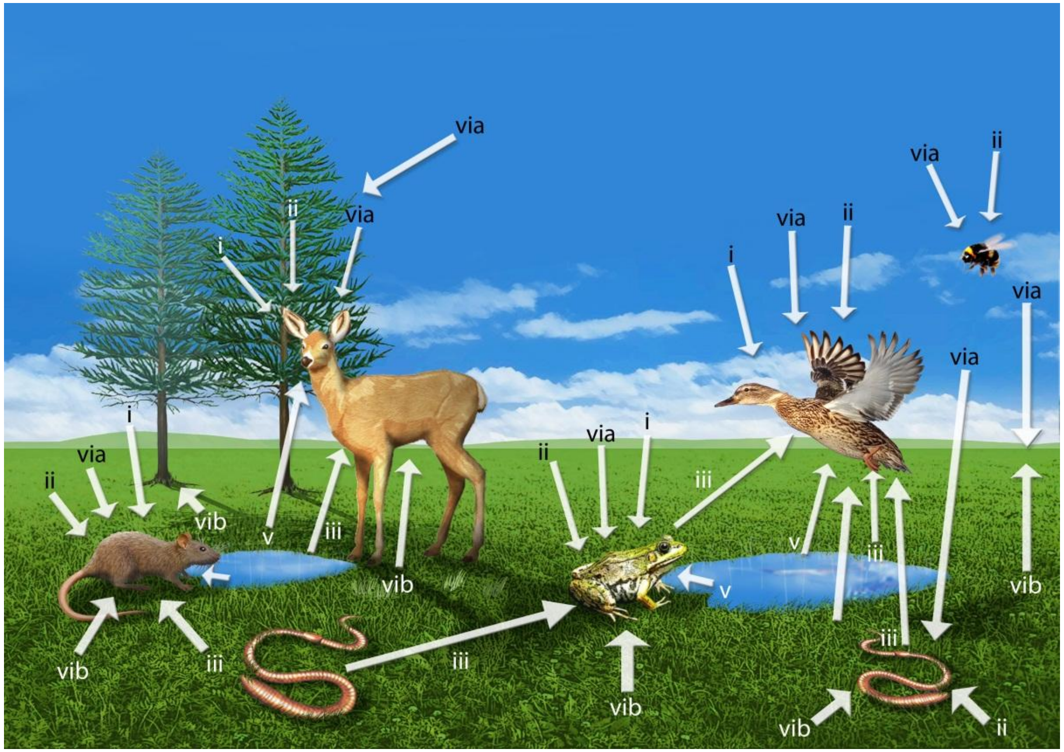
ICRP "Reference Animals and Plants" in red

# Radionuclides

- Radionuclides to cover expected EIA scenarios, e.g. sources:
  - TENORM
  - Routine release (reprocessing, power production)
  - Accidents
  - High level waste repository
- Basis for transfer data collation, radioisotopes of these elements basis for dosimetry work.

| | |
|---|---|
| Ag | Silver |
| Am | Americium |
| C | Carbon |
| Cd | Cadmium |
| Ce | Cerium |
| Cl | Chlorine |
| Cm | Curium |
| Co | Cobalt |
| Cs | Caesium |
| Eu | Europium |
| H | Tritium |
| I | Iodine |
| Mn | Mangenese |
| Nb | Niobium |
| Ni | Nickel |
| Np | Neptunium |
| P | Phosphorus |
| Pb | Lead |
| Po | Polonium |
| Pu | Plutonium |
| Ra | Radium |
| Ru | Ruthenium |
| S | Sulphur |
| Sb | Antimony |
| Se | Selenium |
| Sr | Strontium |
| Tc | Technetium |
| Te | Tellurium |
| Th | Thorium |
| U | Uranium |
| Zr | Zirconium |

# Exposure pathways




- Fig. 1.3 Terrestrial exposure pathways; i) Inhalation of particles or gases ii) Contamination of fur/feathers/skin iii) Ingestion lower trophic levels v) Drinking contaminated water vi) External exposure through a) air or b) soil

# Biological transfer (as considered in ERICA)

For the terrestrial ecosystems the CRs are defined as:

$$CR_{b,i}\ (dimensionless) = C_{b,i}/C_{soil,i}$$


where,
$CR_{b,i}$ = Concentration ratio for reference organism b and radionuclide i;
$C_{b,i}$ = Activity concentration of radionuclide i in whole body of reference biota (Bq kg$^{-1}$, fresh weight);
$C_{soil}$ = Activity concentration of radionuclide i in surface soil (Bq kg$^{-1}$ d.w.)

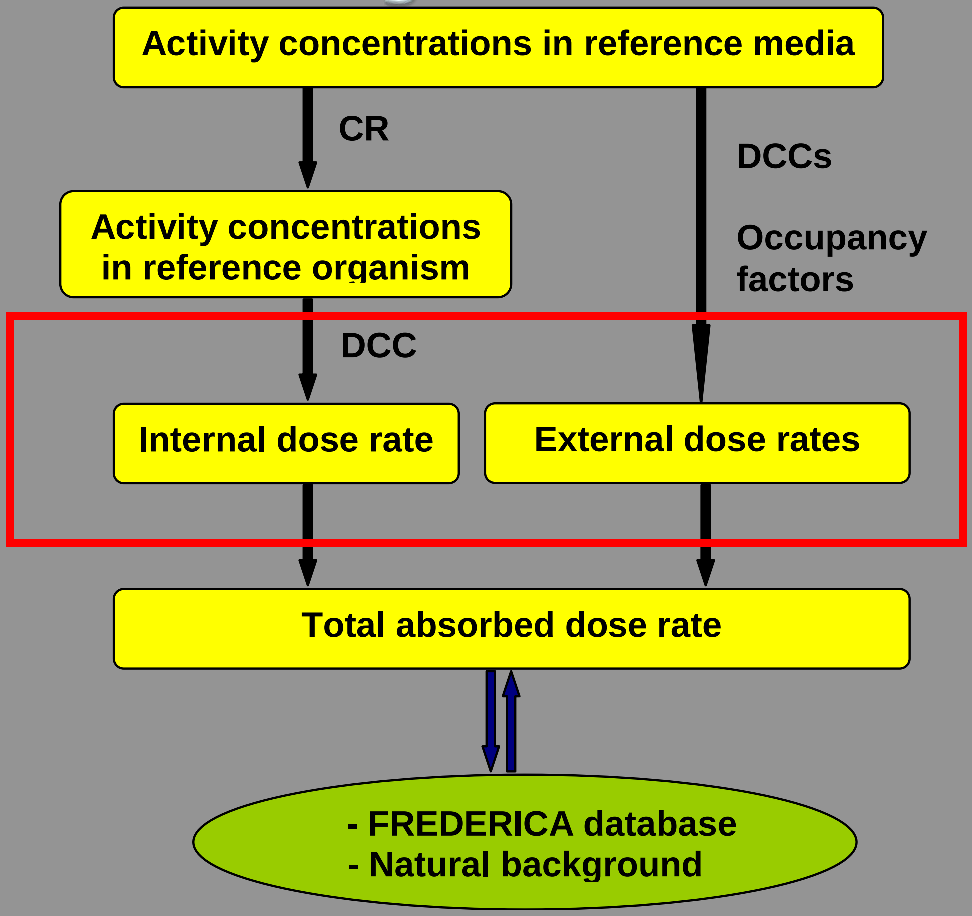
For the aquatic ecosystems the CR, commonly also known as Concentration Factors (CF), are defined as:

$$CR_{b,i}\ (dimensionless\ or\ l\ kg^{-1}) = C_{b,i}/C_{aq}$$

Where
$CR_{b,i}$ = Concentration Factor for reference organism b and radionuclide i;
$C_b$ = Activity concentration of radionuclide i in whole body of reference biota (Bq kg$^{-1}$, fresh weight);
$C_{aq}$ = Activity concentration of radionuclide i in aqueous phase (Bq l$^{-1}$ or Bq kg$^{-1}$) - normally filtered water.

- This is a drastic simplification because there is no consideration of water chemistry, physicochemical form etc. and there is an underlying assumption that the system is in equilibrium **BUT**
- The approach
  - uses empirical information and can therefore be considered to represent in situ conditions
  - is easily understood
  - is consistent with human impact assessment methodology

# Estimating doses to biota



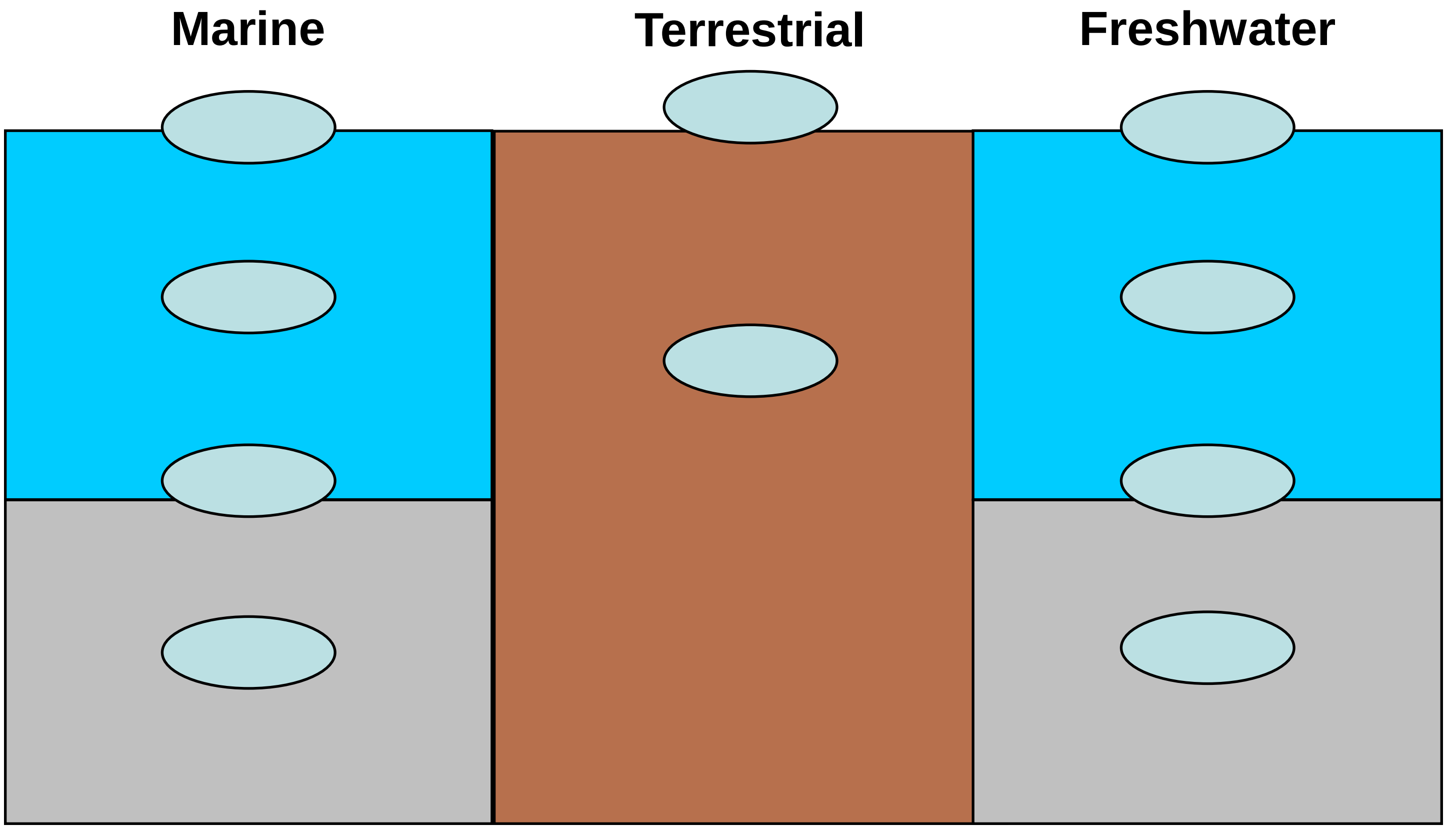

- **Dose Conversion Coefficients are used to derive internal (eq.1) and, together with "occupancy factors" (v) - external (eq.2) dose-rates for reference organisms.**

$$\dot{D}^{j}_{\mathrm{int}} = \sum_i C_i^j * DCC^{j}_{\mathrm{int},i} \qquad \text{(Eq. 1)}$$

$$\dot{D}^{j}_{ext} = \sum_z v_z \sum_i C^{ref}_{zi} * DCC^{j}_{ext,zi} \qquad \text{(Eq. 2)}$$

**DCC = Dose-rate (µGy/h) per activity concentration (Bq/kg)**

# Occupancy factors



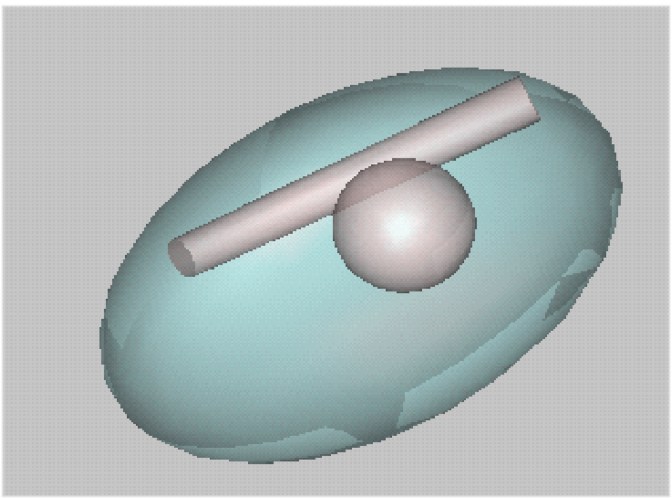

Fraction of time spent by organism at different locations within its habitat

# Dosimetry : dose-concept

- Basic unit = absorbed dose (Gy) but
  - Different types of radiation are known to produce different degrees of effect in the same biological tissue, for the same absorbed doses, for many types of organisms.
- Key quantity = Absorbed fraction energy emitted by a radiation source that is absorbed within the target

# Ecodosimetry

- Methodology also used for ICRP's "Reference animals and plants."



$$\phi = \frac{\text{photon energy absorbed by target}}{\text{photon energy emitted by source}}$$

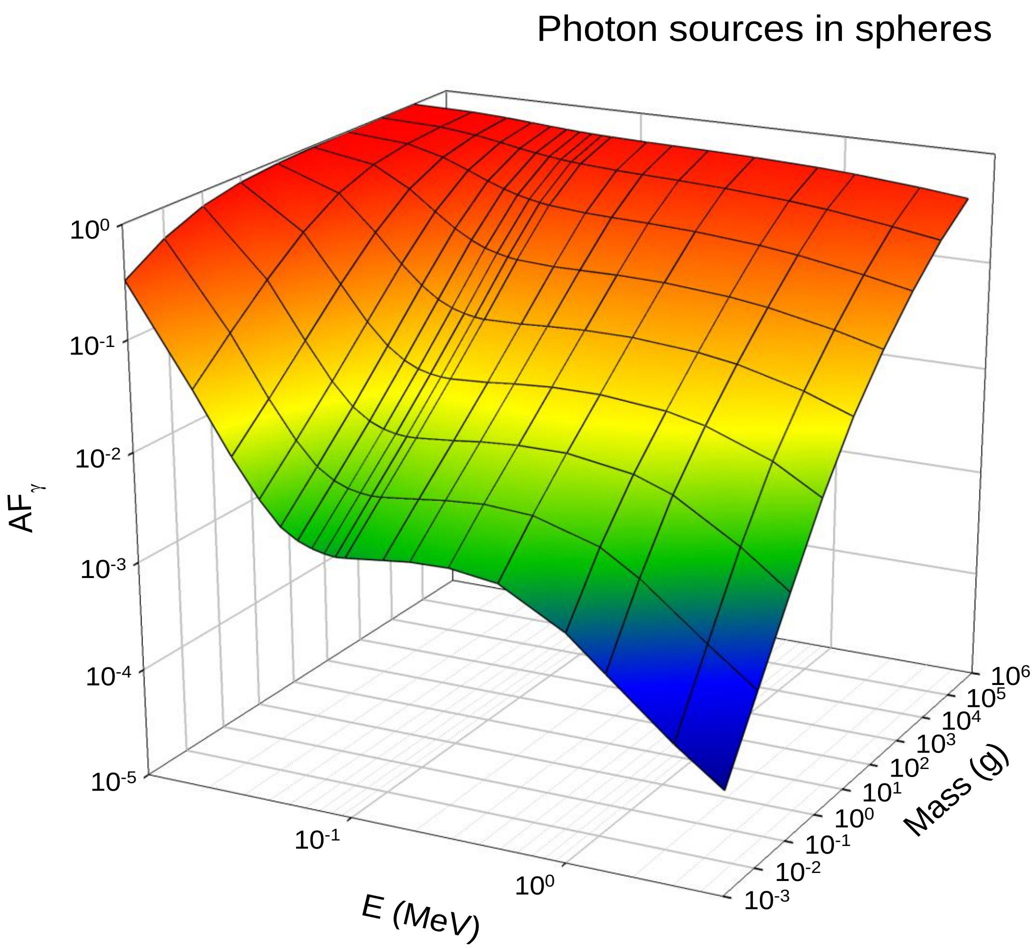
- Data pertaining to absorbed fractions ($\phi$) have been calculated using Monte Carlo radiation tranport models for

  a) Spherical and elliptical forms in water (9 shapes)

  b) masses in the range from 1 mg to 1 tonne

  c) photon/electron energies in the range from 10 keV to 5 MeV

# Results: Photon ϕ (sphere)




**ϕ is a function of**

- **Energy**
- **Mass**

**Large mass and low energy**

**ϕ ➔ 1.**

**Small mass, and High energy,**

**ϕ ➔ 0**

# Dosimetry

- Internal DCC

$$DCC_T^{\text{int}} = 5.75 \times 10^{-4} \cdot \sum_i \Phi_T(E_i) \cdot E_i \cdot y_i$$

*Ei* is the energy of component <i> of emitted radiation (MeV); *yi* is the yield of emitted radiation of energy Ei (dis-1); *ΦT(Ei)* is the absorbed fraction in the target for energy Ei; $5.75 \times 10^{-4}$ is the factor to account for conversions of MeV to Joules and seconds to hours

- External DCC (where density differences between media are small)

$$DCC_T^{ext} = 5.75 \times 10^{-4} \cdot \sum_i (1 - \Phi_T(E_i)) \cdot E_i \cdot y_i$$

- For terrestrial – explicit MC simulations for selected "target–source configurations"

# Note on DCCs

- We also calculate **weighted total dose rates** (in µGy/h)
- **Radiation weighting factors** (dimensionless):

$$DCC_{int} = wf_{low\beta} \cdot DCC_{int,low\beta} + wf_{\beta+\gamma} \cdot DCC_{int,\beta+\gamma} + wf_{\alpha} \cdot DCC_{int,\alpha}$$
$$DCC_{ext} = wf_{low\beta} \cdot DCC_{ext,low\beta} + wf_{\beta+\gamma} \cdot DCC_{ext,\beta+\gamma}$$

**Where:**
**wf** = weighting factors for various components of radiation (low beta, $\beta$ + $\gamma$ and alpha)
**DCC** = dose conversion coefficients in µGy/h per Bq/L or kg

# Radiation weighting factors

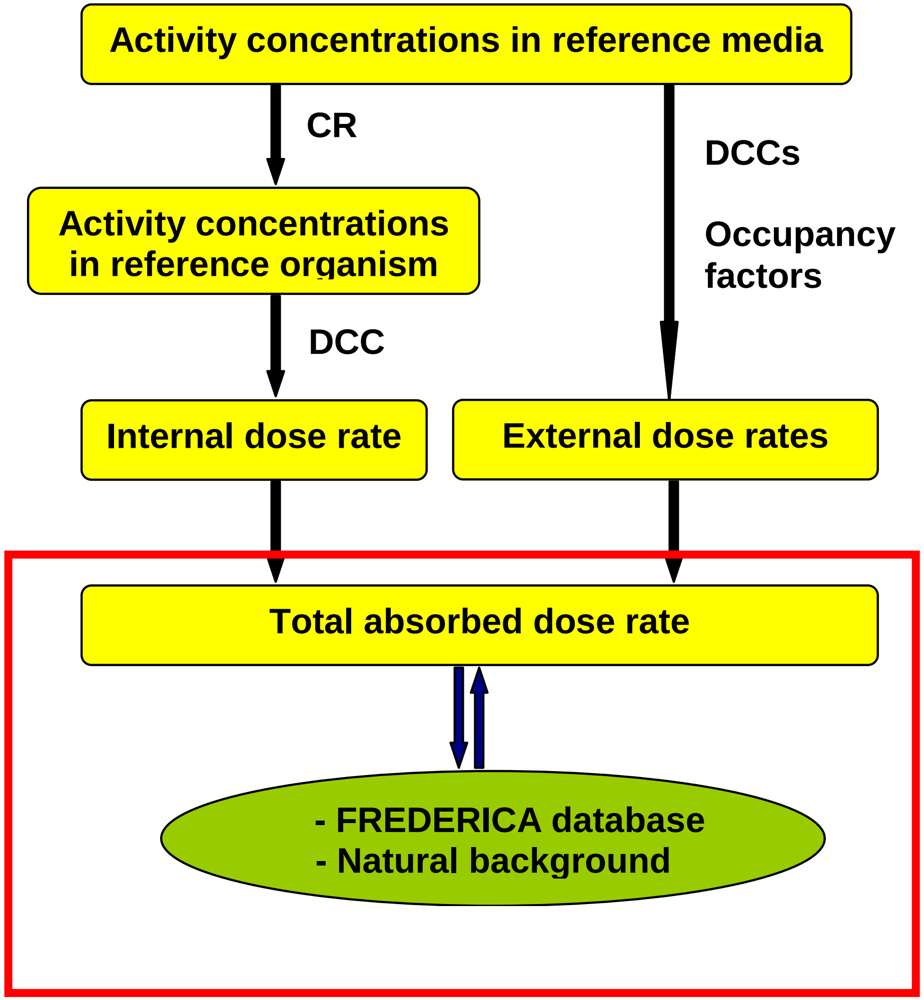
- For humans, $\alpha$–rad ”weighting” factor = 20 but this value is specific to stochastic effects.
- For plants and animals more emphasis placed upon ’endpoints’ that are relevant for the integrity of the population – mortality, morbidity, reproduction effects
- Based upon (Relative Biological Effectiveness) RBE studies –

$$\text{RBE} = \frac{\text{Absorbed dose of reference radiation required to produce a given biological effect}}{\text{Absorbed dose of specified radiation required to produce the same effect}}$$

- RBE is dependent upon dose-rate, species, endpoint studied etc.
- Statistical treatment of data ➔
  - circa 4 = reference value for alpha radiation weighting factor
  - Chambers et al. (2006) – up to 10 for deterministic, population relevant endpoints.

Chambers D, Osborne R, Garva A. 2006. Choosing an alpha radiation weighting factor for doses to non-human biota. J. Environ. Radioactivity, 87(1):1-14.

# Dose-effect relationships




- Total dose-rate (eq.3) is used to make a prognoses about the potential biological effects in exposed plants and animals

$$\dot{D}^{j}_{total} = \dot{D}^{j}_{\mathrm{int}} + \dot{D}^{j}_{ext} \quad \text{(Eq. 3)}$$

# Current understanding of radiation effects (within the context of the human animal)

- The principal cellular target for biological effects = chromosomal DNA
- Effects at a sub-cellular level
  - a high proportion of radiation induced damage in DNA is represented by the occurrence of <u>complex clusters</u> of chemical alterations
  - Frequency and complexity of clusters depends on LET
- Error-prone repair of double strand breaks best explains chromosome aberrations, gene mutation and cell killing

# Current understanding of radiation effects II

- Compelling evidence that changes in DNA damage response/repair and apoptotic/cell cycle control are closely associated with tumor development
- Recent radiobiological work on
  - Induction of gene and chromosomal mutations at low doses.
  - Genomic instability : consequences expressed after many post irradiation cell cycles

# Tissue and organ effects

- Stochastic effects
  - Single cell death = no consequences for tissues, but mutation in a single cell ➔ tumorogenesis ➔ cancer
  - No threshold, frequency related to dose
- Early or late tissue or organ reactions
  - larger doses ➔ substantial amount of cell killing ➔ detectable tissue reactions
  - Structure of organs and tissue plays a role in response
  - Reserve capacity in organs ➔ high tolerance to partial irradiation
- Radiation tumorogenesis
  - Weak ‘promoter’ of tumour development, likely acts in earliest phase
- Mutations causing heritable diseases
  - Principal genetic effects in humans = multi-system developmental abnormalities rather than single gene diseases.

# Underpinning dose-effects analysis

## FREDERICA Radiation Effects Database

| Reference ID Number | Article Type | QC Score DETAILS |
|---|---|---|
| 296 | Journal | B |

**Reference**

Baptist, J.P., Wolfe, D.A., and Colby, D.R. , (1976) , Effects of chronic gamma radiation on the growth and survival of juvenile clams (Mercenaria mercenaria) and scallops (Argopecten irradians). , Health physics. , 30 , , 79-83.

**Keywords**

**Reference Language** | **Translation into English available**

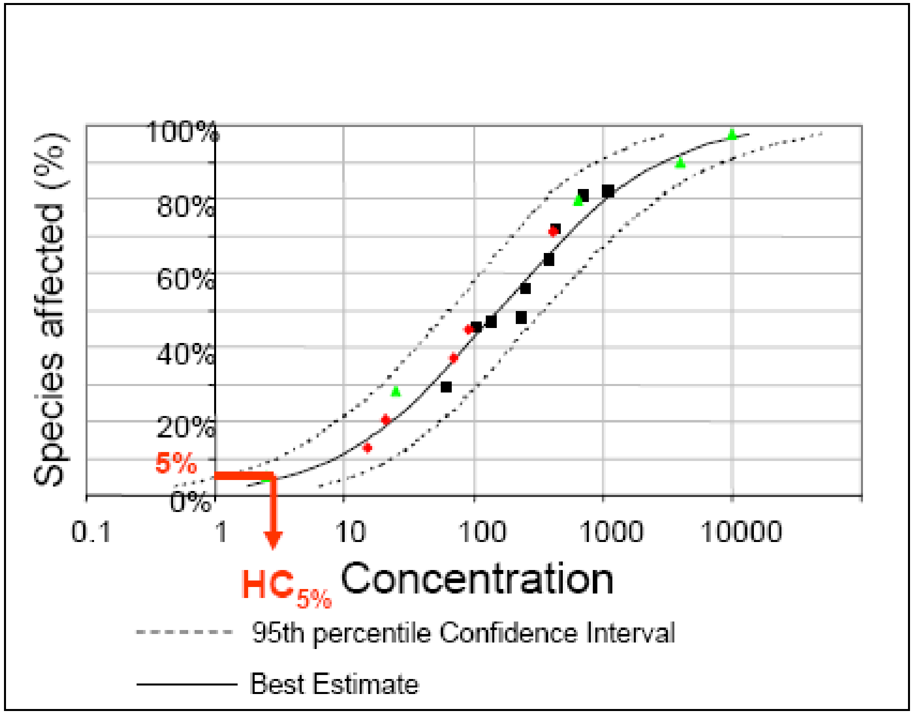
- Large literature review : >1200 references; circa 30 000 data
- Various animal and plant categories
- Different endpoints : mortality, morbidity, reproduction, mutation
- Acute and chronic exposure data but focus on chronic (environmentally relevant) data.
- Quality Control of data

# Selected observations from the database

- Fish, mammals and terrestrial plants have been the most studied
- 36 % of data pertained to chronic irradiation
- Earlier work on the database (Real et al., 2004) :
  - the threshold for statistically significant effects in most studies is about 100 μGy $h^{-1}$.
  - responses then increase progressively with increasing dose rate and usually become very clear at dose rates >1000 μGy $h^{-1}$ sustained for a large fraction of the lifespan.

Real, A., Sundell-Bergman, S., Knowles, J.F., Woodhead, D.S. & Zinger, I. (2004). Effects of ionising radiation exposure on plants, fish and animals : relevant data for environmental radiation protection. Journal of Radiological Protection, 24, pp. A123-A138.

# Screening Dose-rate

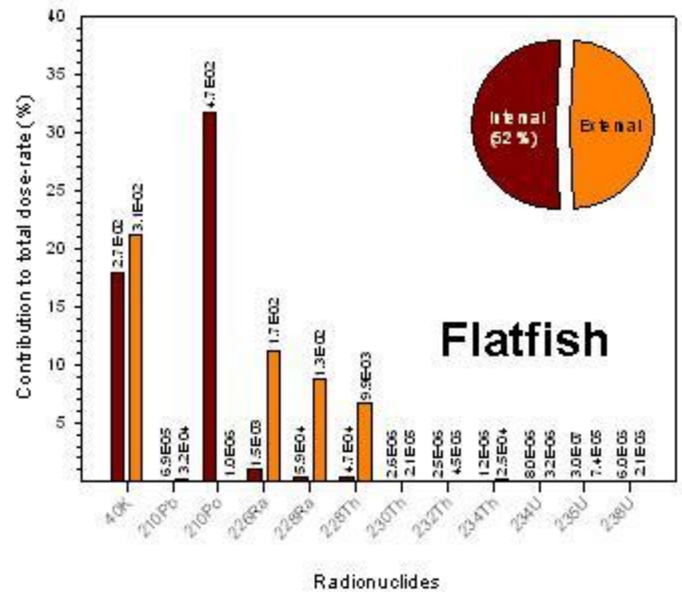



- **EU TGD used : protective of function and structure of ecosystem**
- **Dose-response curves from different extracted from the FREDERICA database**
- **Dose-effect curves for individual studies $EDR_{10}$ = dose-rate which gives a 10 % effect in endpoints.**
- **Species Sensitivity Distribution → "Hazardous Dose-rate 5 %" – (10 % effect in 5 % of species)**
- **Safety factor of 5 used (uncertainty and extrapolation) to derive a PNEDR.**
- Screening dose rate (PNEDR) = 10 µGy/h
- **Nominally portects structure and function of ecosystem but believed to be protective of sensitive endpoints (MB, RC) in sensitive species.**

**Species Sensitivity Distribution. The example shows the five percent protection level and the corresponding HC5 (Hazardous Concentration 5%) used to determine the PNEC.**

# Natural Background

- ERICA deals with incremental dose-rate i.e. exposures that do not include background dose-rates
- Pentreath (2002) suggested that only two reference points can be utilised, in a practicable way to assess radiation impacts in the environment
  - natural background dose-rates and
  - dose-rates known to have specific biological effects on individuals/populations.




In ERICA Background dose-rates simply used as a means of contextualising dose-rate data.

Pentreath R J 2002 Radiation protection of people and the environment: developing a common approach *J. Radiol. Prot.* **22** 45–56.

# Special issues for NORM with regards to EIA

- NORM/TENORM wastes differ significantly from radioactive wastes from the nuclear industry in terms of:
  - source geometry, location and the types of dispersion-transfer models that need to be applied
  - total amount: NORM/TENORM residues are usually bulk materials,
  - ambient conditions: open to weather and uncontrolled access

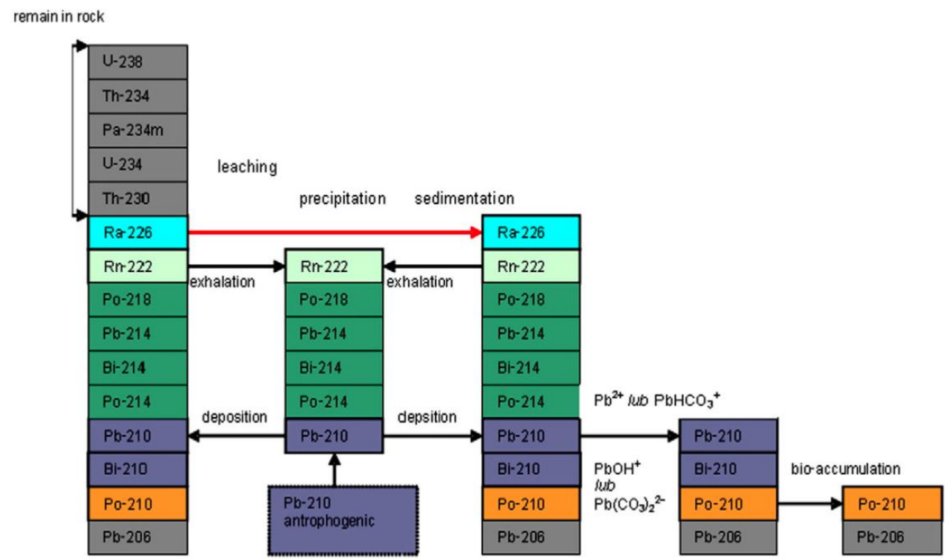
Michalik, B, Brown J, Krajewski P (2013). The fate and behaviour of enhanced natural radioactivity with respect to environmental protection. Environmental Impact Assessment Review 38, 163-171.

# Chemical toxicity

- In the case of long lived radionuclides, especially uranium, chemical toxicity can significantly contribute to the total risk.
  - All short lived daughters, in spite of them being isotopes of toxic metals e.g. Pb, occur in such low concentrations by mass that their chemical interaction and derived chemical toxicity is negligible compared with their radiotoxicity
- This opens up a whole new area of consideration – multiple stressors and how these should be treated (in terms of combining risk) in a regulatory context – a theme of ongoing and intense scientific discussion

# Long decay series

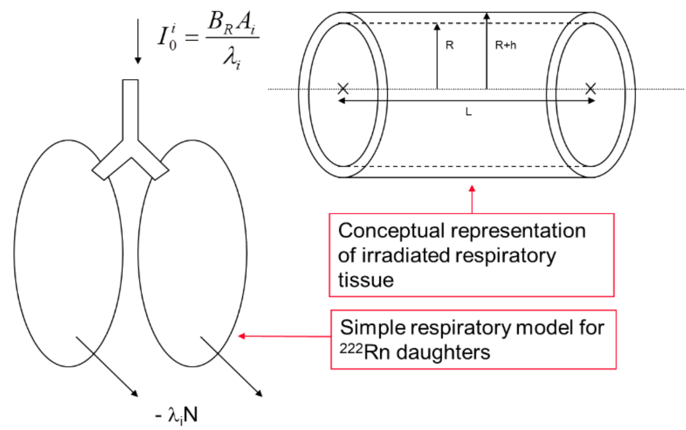
- Differential migration and biological transfer of the various decay series radionuclides. From this point of view, the most important radionuclides are: $^{226}Ra$, $^{228}Ra$, $^{228}Th$ and the long lived radium-226 daughters $^{210}Pb$ and $^{210}Po$, which differ greatly in terms of chemical properties from their parents i.e. uranium, thorium.




- Ingrowth is an important factor
- The assumption in ERICA is arguably tenable in many instances for U-238 and Th-232 decay series:
  - Radionuclide decay chains were truncated at the first radionuclide with a half-life of more than10 days:-The DCCs of shorter-lived radioactive progeny in the decay chain were then amalgamated with the DCC of their longer-lived parent.
  - Exception may be Radon

# Doses from radon

- Vives i Batlle developed a model based on allometrically derived respiration rates and target tissue masses, designed for calculating $^{222}Rn$ daughter dose rates to sensitive tissues and the whole body of terrestrial animals and plants.




Animals

| Organism | M (kg) | a (m) | b (m) | c (m) | $\phi$ ($m^3$ $s^{-1}$) | $DCC_B$ | $DCC_{TB}$ | $DCC_L{}^a$ | $DCC_{WB}$ |
|---|---|---|---|---|---|---|---|---|---|
| Amphibian (ICRP Frog) | 3.1E-02 | 8.0E-02 | 3.0E-02 | 2.5E-02 | 5.9E-07 | 1.3E+01 | 1.4E+00 | 3.1E-01 | 3.7E-03 |
| Reptile (FASSET snake) | 7.4E-01 | 1.2E+00 | 3.5E-02 | 3.5E-02 | 6.3E-06 | 1.6E+01 | 1.7E+00 | 1.3E-01 | 1.7E-03 |
| Mammal (ICRP Rat) | 3.1E-01 | 2.0E-01 | 6.0E-02 | 5.0E-02 | 3.2E-06 | 1.5E+01 | 1.6E+00 | 1.6E-01 | 2.1E-03 |
| Mammal (ICRP Deer) | 2.5E+02 | 1.3E+00 | 6.0E-01 | 6.0E-01 | 6.9E-04 | 3.8E+01 | 4.1E+00 | 4.0E-02 | 5.6E-04 |
| Bird (ICRP Duck) | 1.3E+00 | 3.0E-01 | 1.0E-01 | 8.0E-02 | 9.4E-06 | 1.7E+01 | 1.9E+00 | 1.2E-01 | 1.5E-03 |
| Mammal (FASSET Marine) | 1.8E+02 | 1.8E+00 | 4.4E-01 | 4.4E-01 | 5.4E-04 | 3.6E+01 | 3.8E+00 | 4.2E-02 | 5.9E-04 |
| Reptile (ICRP Marine Turtle) | 1.4E+02 | 8.5E-01 | 3.9E-01 | 8.0E-01 | 4.3E-04 | 3.4E+01 | 3.7E+00 | 4.4E-02 | 6.2E-04 |
| Mammal (FASSET Freshw.) | 3.9E+00 | 3.3E-01 | 1.5E-01 | 1.5E-01 | 2.3E-05 | 2.0E+01 | 2.1E+00 | 8.9E-02 | 1.2E-03 |


Vives i Batlle, J., Copplestone, D. and Jones, S.R. (2012). Allometric methodology for the assessment of radon exposures to wildlife. *Science of the Total Environment*. **427-428**: 50–59