Chapter 9

Annual effective dose from natural environmental radiation

This chapter presents a method for estimating the annual effective dose to the European population due to exposure to natural environmental radiation. Essentially, it extends methods from previous chapters for estimating internal and external dose from terrestrial and cosmic radiation. However, it should be noted that doses from ingestion and inhalation (apart from indoor radon and progeny) of terrestrial radionuclides are taken from literature. For the first time, the availability of European population maps makes it possible to give an overall European estimate of the annual dose. In this approach, collective doses were estimated in each 10 km × 10 km cell for most European countries by multiplying the annual effective dose by the number of persons living in each cell. These estimates took into account indoor occupancy rates, shielding, and elevation above sea-level which are important factors for estimating doses from radon, external radiation and cosmic radiation, respectively.

We present details for most European countries on the various contributions from natural radiation to dose. Notably, doses from radon and progeny are the major contributors in all these countries, and on the European level they represent about 60 % of the total dose of 3.2 mSv/a, as compared to about 50 % of the total dose of 2.4 mSv/a on a global basis. Between the European countries considered here, total estimated doses range from 1.48 mSv/a in the Netherlands to 5.83 mSv/a in the Czech Republic. This fourfold increase in total dose essentially reflects the tenfold increase in radon doses from 0.43 mSv/a in the Netherlands to 4.47 mSv/a in the Czech Republic. Moreover, within countries exposure and dose may vary significantly, reflecting the varied regional geology which affects both external radiation and radon exposures. In regions where the underlying geology is composed of granites, exposures due to external radiation and radon can be comparatively high. Due to a lack of representative data, certain components of exposure, such as those due to natural radionuclides in building materials, are not included here. Finally, in keeping with the core rationale of this Atlas, this chapter deals only with doses from natural sources; that is, no comparison is made here with doses from anthropogenic sources such as nuclear accidents or medical doses. As indoor radon exposures are due to the design, construction and usage of buildings, it can be argued that although radon itself is natural, the doses from indoor radon are also anthropogenic.

Long-exposure photograph capturing the apparent motion of stars and planets (Angus, Scotland, UK).
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9.1 Introduction

The overall goal of this Atlas is to estimate the annual effective dose that the European population may receive from natural radiation.

In general, estimating dose to the public is not based on direct measurements, but on environmental data and models for environmental exposure scenarios. Different approaches exist to estimate the dose, but they mainly depend on data availability (UNSCEAR, 2000: Annex A). Indeed, in this work, effective doses have been estimated by combining all the information from the various natural sources of exposure discussed in previous chapters.

Table 9-1 summarises the main sources of natural exposure for the general public and their contribution to internal and external doses. External exposure arises from radiation sources located outside the human body; it is mainly due to gamma radiation (see Section 2.1). As opposed to external exposure, internal exposure occurs when the sources of ionising radiation are located inside the human body. This is due to the intake of radionuclides through ingestion (food and drinking water) or inhalation of radionuclides.

Unfortunately, except for inhalation of indoor radon and its progeny, data on ingestion and inhalation exposures have not been collected for this study (Table 9-1). For the missing exposure sources, however, data from literature have been used.

Thanks to the availability of European population maps (Batista e Silva et al., 2013a, 2013b; Lavalle & Jacobs-Crisioni, 2016), it has been possible to estimate a population-weighted average of the annual effective dose due to natural sources for the European countries considered as well as for all of them together, giving, therefore, an overall European estimate.

9.2 Materials and methods

9.2.1 Dose calculation

In order to estimate the annual dose received from natural radiation sources for the European countries considered, as well as for all of them together, the following procedure has been followed, giving, therefore, a European estimate:

a. resampling all input data to 10 km × 10 km resolution to compare all the information included in the European maps developed in this Atlas;

b. estimating the collective doses (cosmic, radon and terrestrial) in each 10 km × 10 km grid cell, by multiplying the annual effective dose with the number of people living in that cell;

c. estimating the population-weighted average annual effective doses (cosmic, radon and terrestrial) for the European countries considered, as well as for all of Europe; and

d. by considering literature data for missing exposure sources, estimating the population-weighted average total annual effective doses, for each European country considered, as well as for all of Europe.

9.2.2 Input data

a. Cosmic sources

Cosmic radiation

The Joint Research Centre of the European Commission has developed the European Annual Cosmic-Ray Dose Map (at 1 km × 1 km resolution); it is described in detail in Chapter 8. The effective dose due to cosmic radiation (photons, direct ionising and neutron components) at ground level has been calculated following methods used by UNSCEAR and based only on elevation data (UNSCEAR, 2008: Annex B).

The map displays the annual effective dose (external dose) that a person could receive from cosmic radiation (photons, direct ionising and neutron components) at ground level, if she/he spends all the reference time at that elevation, considering a shielding factor of 0.8 and an indoor occupancy rate of 0.8 (UNSCEAR, 2000, Annex B).

The 1 km × 1 km grid-cell resolution was reduced to 10 km × 10 km. This upscaling process was performed using the 'aggregate' tool in ArcGIS® (Esri, 2011), so that the output cell contains the sum of the input cells (1 km × 1 km) enclosed by that cell.

Exposure sources	**Doses**		
	Internal		**External**
	Ingestion	**Inhalation**	
Terrestrial radionuclides	^{40}K, uranium and thorium series	^{40}K, uranium and thorium series	Terrestrial radiation (^{40}K, uranium and thorium series)
	Radon, thoron and their progenies	Radon and its progeny	Radon, thoron and their progenies
		Thoron and its progeny	
Cosmic radiation	Cosmogenic radionuclides	Cosmogenic radionuclides	Directly ionising, photon and neutron component

Table 9-1.
Main sources of natural exposure for the general public and their contribution to internal and external doses. The data available at the European level and presented in this Atlas are highlighted in darker green.
Source: EANR, EC-JRC, 2019.

Cosmogenic radionuclides

As discussed in Chapter 8, cosmogenic radionuclides are relevant mainly as tracers. Only a few cosmogenic radionuclides, viz. ^{14}C, ^{3}H, ^{22}Na and ^{7}Be, contribute to radiation doses through ingestion (food and water) and inhalation. However, their contribution to the public exposure from natural radiation sources is less than 0.1% (UNSCEAR, 2008: Annex B).

Unfortunately for this Atlas, no data on concentrations of cosmogenic radionuclides in air, food and water have been collected at the European level. Therefore, the annual effective dose due to cosmogenic radionuclides could not be estimated for European countries, and it has been considered as a fixed value, viz. that as reported by UNSCEAR (2008: Annex B), estimated at 0.01 mSv/a globally.

b. Terrestrial sources

Terrestrial radiation

The European Annual Indoor Radon Dose Map (at 10 km × 10 km resolution) displays the annual effective dose (external dose) that a person could expect to receive from terrestrial radiation, if she/he were to spend all the reference time in a location in which the soil has fixed uranium, thorium and potassium concentration, considering an indoor occupancy rate of 0.8 and a shielding factor of buildings of 1.4.

The dose has been estimated using geochemical concentration of uranium, thorium and potassium in soils, according to the UNSCEAR formula (UNSCEAR, 2008: Annex B), under some assumptions. More details on the methodology are provided in Chapter 4.

Radon (^{222}Rn)

The European Annual Indoor Radon Dose Map displays the annual effective dose (internal dose) that a person may receive from radon inhalation when spending 0.8 of the time indoor at ground floor of a dwelling. The dose coefficient used in this work is the one proposed by UNSCEAR in 2000 (UNSCEAR, 2000: Annex A) and an equilibrium factor of 0.4. More details on the methodology are provided in Section 5.4. Assuming, for lack of more detailed data, that all persons spend 0.8 of their time indoor at ground floor in dwellings, the dose might be overestimated. For some countries or areas (such as large cities), where many people live in flats on higher floors, the dose might be overestimated; whereas for countries where most people live in detached or semi-detached houses, overestimation will be limited. However, this is the best that could be achieved at the time this Atlas was written.

Thoron (^{220}Rn)

Unfortunately, no data on thoron concentration in indoor air could be collected for this Atlas, because varying amounts of such data. Therefore, the annual effective dose due to inhalation of thoron and its progeny could not be estimated for European countries, and it has been considered as a fixed value, viz. that reported by UNSCEAR (UNSCEAR, 2008: Annex B), estimated at global level as 0.1 mSv/a.

Terrestrial Radionuclides (other than radon)

Radionuclides of the uranium and thorium series and ^{40}K enter human beings through inhalation and ingestion.

Natural radionuclides are present in dust particles and can be inhaled. Inhalation of natural radionuclides, other than radon and its decays products, gives rise to a minor contribution, less than 0.01 %, to the dose due to natural radiation sources (UNSCEAR, 2008: Annex B).

Ingestion of ^{40}K and of ^{238}U and ^{232}Th series radionuclides comes from foods and drinking water. The effective dose received by ingestion depends on the consumption rates of food and water and on the radionuclides concentrations, and varies widely.

Unfortunately, no data on concentrations of radionuclides in air, food and water have been collected at European level for this Atlas. Therefore, the annual effective dose (internal dose) due to ingestion and inhalation of terrestrial radionuclides (other than radon) could not be calculated for European countries, and it has been estimated as a fixed value, the same as reported in UNSCEAR (UNSCEAR, 2008: Annex B), assessed at global level as 0.29 mSv/a.

c. Population

The European Population Map 2006, created by the Joint Research Centre of the European Commission and by the Centro de Estudos de Geografia e Ordenamento do Território of Portugal (Batista e Silva et al., 2013a, 2013b; Lavalle & Jacobs-Crisioni, 2016), was used as reference for estimating dose. This database was chosen because it is the most recently updated European population grid map; for many European countries, data are still distributed at coarser geographical units such as municipalities.

The data are organised in a digital raster grid that reports the number of residents (night-time population) in 100 m × 100 m grid cells. It has been produced by downscaling census population data, at the finest available resolution, to the 100 m × 100 m grid-cell level given pycnophylactic interpolation constraints (redistribution or 'disaggregation' of data given on input support like administrative polygons into grid cells, preserving total 'volume', i.e. population number in this case). This downscaling was performed using data on land use (a refined version of the Corine Land Cover data from 2006) and soil-sealing. In addition, the final outcome of this cartographic exercise was validated against reference data.

Here, this resolution level (100 m × 100 m cells) was reduced to 10 km × 10 km to compare it with the information included in the European maps (10 km × 10 km cells). This upscaling process was performed using the 'aggregate' tool in ArcGIS® (Esri, 2011), so that the output cell contains the sum of the input cells (100 m × 100 m) enclosed by that cell.

9.3 Results

Table 9-2 and the pie charts in Figure 9-1 invite several observations for each source of natural radiation:

- **Radon (^{222}Rn) and its progeny** represent the most important contribution to the dose from natural sources of radiation due to inhalation. In the budget estimated for Europe, they amount to about 60 % of the total dose, while at global level to about 50 %. This contribution would change if newer dose conversion factors were applied (see Section 5.4.4 for further details about dose conversions factors). Thoron (^{220}Rn) progeny generally contribute less, although in certain situations (e,g. with clay as building material), they may even be dominant. The contribution of radon and its progeny differs significantly between countries, from about 30 % in the Netherlands and Cyprus to more than 75 % in the Czech Republic and Finland. This reflects differences in the geogenic radon contribution due to different geology. Moreover, different construction styles play a role, as they are influenced by climate: air exchange (which is inversely related to indoor radon) can, on average, be expected to be lower in Northern than in Southern Europe. (Please note that these percentages would change if different dose conversion factors were applied for radon and its progeny.)
- The second important contribution is due to **terrestrial external radiation**, on average. The value estimated at the European level is 0.50 mSv/a, similar to the one at global level, 0.48 mSv/a. In Europe, terrestrial external radiation represents 15 % of the total dose due to natural radiation. At country level, terrestrial external radiation presents different values due to varying geology, from 0.85 mSv/a in Portugal, via 0.6 mSv/a in Bulgaria, Croatia, Sweden and the Czech Republic, to the lowest values, around 0.3 mSv/a, found in Poland, the Netherlands, Denmark and Cyprus.
- The dose due **to cosmic radiation** depends essentially on altitude above sea level, so that low-lying countries, e.g. the Netherlands, Denmark and Baltic countries, are less affected than Turkey, Switzerland or Austria. The value estimated at European level is 0.34 mSv/a, similar to the global one of 0.38 mSv/a. For European countries, it ranges from 0.31 mSv/a in Denmark, Estonia, Finland, Ireland, Latvia, the Netherlands and Sweden, to 0.41 mSv/a in Switzerland and 0.42 mSv/a in Turkey.
- For the **other sources of natural radiation** (terrestrial radionuclides, ingestion-inhalation other that radon; thoron and its progeny; cosmic radionuclides), data from literature have been used, and in total they contribute about 0.39 mSv/a, which represents about 12 % at the European level.

Population-weighted average annual effective doses (mSv)							
Dose	**External**		**Internal (ingestion/inhalation)**		**Internal (inhalation)**		**Total***
Exposure sources	**Cosmic radiation**	**Terrestrial radiation**	**Cosmic radionuclides**	**Terrestrial radionuclides (no radon)**	**Radon and progeny***	**Thoron and progeny**	
World (UNSCEAR 2008)	0.38	0.48	0.01	0.29	1.15	0.1	2.41
Europe	0.34	0.5	0.01	0.29	1.96	0.1	3.20
Country							
Albania	0.34	0.49	0.01	0.29	2.82	0.1	4.05
Austria	0.39	0.54	0.01	0.29	2.53	0.1	3.86
Azerbaijan	na	na	0.01	0.29	na	0.1	
Belgium	0.32	0.46	0.01	0.29	1.54	0.1	2.72
Belarus	na	na	0.01	0.29	na	0.1	
Bosnia and Herzegovina	0.37	0.6	0.01	0.29	na	0.1	
Bulgaria	0.36	0.63	0.01	0.29	2.85	0.1	4.24
Croatia	0.33	0.61	0.01	0.29	2.39	0.1	3.73
Czech Republic	0.35	0.61	0.01	0.29	4.47	0.1	5.83
Cyprus	0.33	0.37	0.01	0.29	0.49	0.1	1.59
Denmark	0.31	0.34	0.01	0.29	2.22	0.1	3.27
Estonia	0.31	0.53	0.01	0.29	2.67	0.1	3.91
Finland	0.31	0.51	0.01	0.29	4.94	0.1	6.16
France	0.33	0.49	0.01	0.29	1.82	0.1	3.04
Germany	0.33	0.47	0.01	0.29	1.44	0.1	2.64
Greece	0.34	0.46	0.01	0.29	1.82	0.1	3.02
Hungary	0.32	0.45	0.01	0.29	2.37	0.1	3.54
Ireland	0.31	0.42	0.01	0.29	2.49	0.1	3.62
Iceland	0.32	na	0.01	0.29	0.34	0.1	
Italy	0.34	0.64	0.01	0.29	2.64	0.1	4.02
Latvia	0.31	0.44	0.01	0.29	1.62	0.1	2.77
Lithuania	0.32	0.42	0.01	0.29	1.39	0.1	2.53
Luxembourg	0.34	0.5	0.01	0.29	2.26	0.1	3.50
Malta	na	na	0.01	0.29	na	0.1	
Montenegro	0.39	0.56	0.01	0.29	na	0.1	
Netherlands	0.31	0.34	0.01	0.29	0.43	0.1	1.48
North Macedonia	0.39	0.63	0.01	0.29	2.98	0.1	4.40
Norway	0.33	0.46	0.01	0.29	2.13	0.1	3.32
Poland	0.33	0.31	0.01	0.29	1.73	0.1	2.77
Portugal	0.33	0.85	0.01	0.29	1.66	0.1	3.24
Romania	0.34	na	0.01	0.29	3.76	0.1	
Serbia	0.34	0.58	0.01	0.29	2.74	0.1	4.06
Spain	0.36	0.53	0.01	0.29	1.79	0.1	3.08
Slovak Republic	0.35	0.54	0.01	0.29	na	0.1	
Slovenia	0.36	0.6	0.01	0.29	3.43	0.1	4.79
Sweden	0.31	0.67	0.01	0.29	3.01	0.1	4.39
Switzerland	0.41	0.55	0.01	0.29	2.69	0.1	4.05
Turkey	0.42	na	0.01	0.29	na	0.1	
United Kingdom	0.32	0.41	0.01	0.29	0.84	0.1	1.97

* Assuming that all persons spend 0.8 of their time indoor at ground floor in dwellings, the dose due to radon inhalation might be overestimated and hence also the total dose for each country considered and for Europe.

Table 9-2.
Population-weighted average annual effective dose (in mSv) for each natural radiation source and their sum for each European country considered and for Europe as a whole. For global comparison, data are reported (UNSCEAR, 2008). na: not available.
Source: EANR, EC-JRC, 2019.

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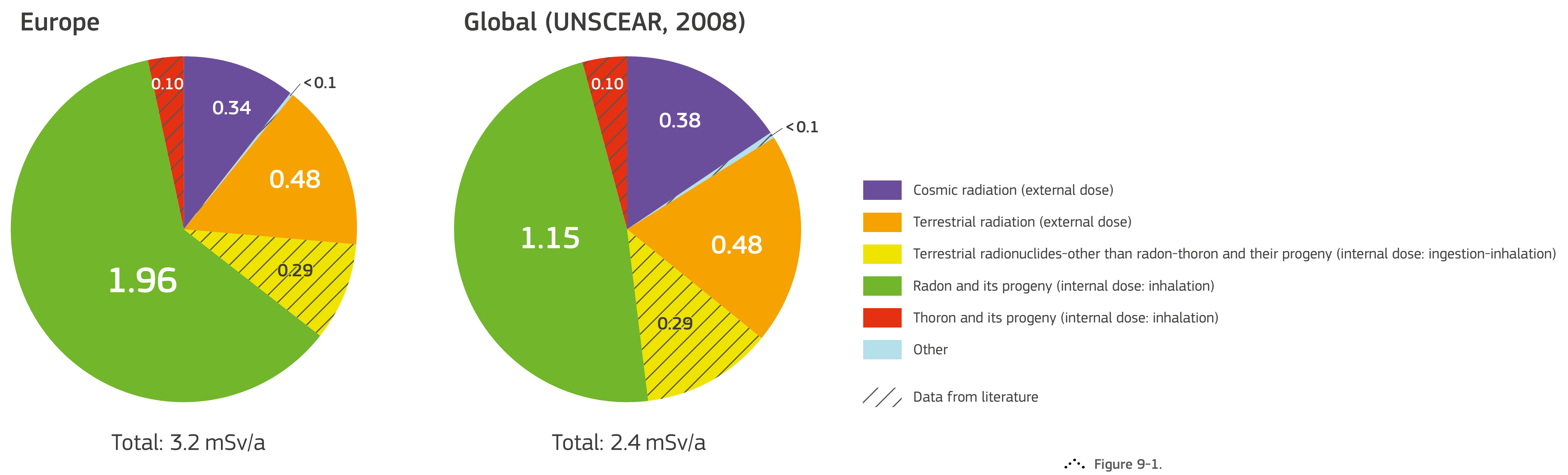

Figure 9-1.
Pie charts showing the population-weighted average annual effective dose (in mSv/a) for each natural radiation source considering European and global populations, respectively.
Source: EANR, EC-JRC, 2019; UNSCEAR, 2008.

Except for radon dose, European and global values are not very different, according to UNSCEAR. The difference observed for radon could be because only ground-floor indoor radon data have been considered at the European level and that, globally, many regions have lighter construction styles than in Europe due to a milder climate, which mitigates the radon hazard.

While Table 9-2 reports country averages, exposure and dose can vary significantly within countries as well. In particular, this applies to countries with varied geology. Comparatively high exposure due to external terrestrial radiation and radon occurs in regions whose geological base is made of certain granites (mainly Variscan and Alpine), such as the Iberian Peninsula, the Massif Central in France and the Bohemian Massif in Austria, the Czech Republic, or the granites of Southern Finland. In the same countries, other regions, mainly sedimentary plains and limestone, have lower exposure. However, also in such regions high-exposure areas can occur, as for example the Swiss Jura (karst limestone) or certain post-glacial formations show. Concerning exposure from cosmic radiation, the evident reason for heterogeneity within a country is the variety between mountains and low-lying plains.

Certain components of exposure could not be discussed here due to lack of data. It can be expected that gamma radiation from building materials would contribute visibly in some areas. Since building materials often come from local sources, typically bricks and limestone from local clay quarries, a geographical trend can be expected for these components as well. The matter is probably more complicated with natural radionuclides in food. These days, only a relatively small fraction of consumed foodstuff is produced locally; this seems to apply increasingly even for rural regions. Therefore, one can expect that the geographical distribution of exposure originating from foodstuff is relatively even, but this is only a hypothesis as long as sufficient data to test it are not available.

Table 9-2 and the pie charts in Figure 9-1 only show doses from natural sources. Qualitatively, comparison with anthropogenic sources would give the following picture:

- Fallout and air contamination from nuclear accidents can contribute locally and over short time periods. The only relevant contribution comes from global fallout of atmospheric nuclear bomb tests made in the 1950s to 1960s, which gave rise to problematic doses in Scandinavia (due to particular food chains) and from the Chernobyl accident on 26 April 1986. In parts of Europe, this led to short-time (days) exposure by inhalation of contaminated air, to mid-term (months) exposure by ingestion of contaminated foodstuff (vegetables, milk), some of which remain effective until today (e.g. certain mushrooms, wild boar), and long-term exposure by gamma radiation of fallout in the ground. However, the geographical exposure pattern is very patchy and heterogeneous (De Cort et al., 1998). Today, the most important contribution is from ground gamma radiation (^{137}Cs). This can amount to few percent of terrestrial radiation in areas of Europe that have been more severely hit (parts of Scandinavia, Austria and Bavaria and spots in Northern Italy, Greece etc.). The situation is different in the heavily affected zones of Ukraine, Belarus and Russia, where relatively high doses are encountered more than 30 years after the accident. Other events led to minor doses over Europe, such as the Fukushima accident on 11 March 2011. Averaged over the years, their contribution is negligible and could not even be visualised in the pie chart.
- On the other hand, medical exposure due to radiotherapy and diagnosis can be considerable and even exceed the natural doses (UNSCEAR, 2008: Annex B). Certain treatments can lead to very high doses, which are considered justified only by weighing risks against benefits. Evidently, this contribution to dose only concerns a fraction of the population, while most are not affected at all.