18. Mapping the terrestrial gamma radiation dose

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The Tellus airborne radiometric data have enabled assessments of environmental radioactivity levels in unprecedented detail across the north of the island of Ireland. Both the natural (geological) and man-made (industrial) contributions to public exposure from ionising terrestrial gamma radiation are considered. Over much of the area the gamma-ray flux is significantly attenuated by peat and organic soil but relatively highly radioactive rocks are exposed in places, notably in the south-east of the surveyed area. The results indicate that across the area the effective dose from terrestrial gamma radiation is everywhere within the acceptable level, subject to the inherent spatial averaging of the measurements. The airborne survey also revealed areas where industry has concentrated or exposed naturally occurring radioactive material, including quarries and fly-ash piles.

Introduction

Since the days of Marie Curie it has been appreciated that exposure to ionising radiation may be hazardous to health. The first definition of a unit of radiation was made in 1928. Units of absorbed dose, the actual energy absorbed in the tissue being irradiated, are now used and are given as 1 J kg^{-1} or 1 gray (Gy). The gray can be used for any type of radiation but it does not express the biological effects from different types of radiation. The absorbed dose rate in air (nGy h^{-1}) is used to indicate the gamma ray intensity in the air from radioactive materials in the earth and atmosphere. *Equivalent* dose rate relates the absorbed dose in human and biota tissue and organs to the effective biological damage. The current SI unit of equivalent dose is the Sievert (Sv). The Tellus airborne radiometric data sets provide estimates of the absorbed dose rate in air (nGy h^{-1}); these may then be converted to equivalent annual dose rate estimates.

Terrestrial gamma radiation (the natural flux from rocks and soils) accounts for approximately 16% of the total annual dose of natural ionising radiation to which the population is exposed (Watson *et al.*, 2005). This terrestrial component arises due to primordial radionuclides that were synthesised during the creation of the planet, and has always accompanied life on Earth. Both humans and biota are exposed to an annual dose rate. The average annual dose to the UK population is estimated to be 2.7 mSv, with 2.2 mSv of this

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coming from natural radiation (Hughes *et al.*, 2005). According to Watson *et al.* (2005), the annual UK exposure from terrestrial gamma radiation is about one third that from the inhalation of radon gas (see Appleton and Hodgson, Chapter 20, this volume; Hodgson and Young, Chapter 2, this volume). The data considered here do not assess the potential exposure from terrestrial radon.

Since the natural flux is largely determined by soil and associated parent geological material, personal annual exposure to terrestrial gamma radiation is determined by the home location, the localities visited and the amount of time spent indoors and outdoors, within a geological framework. The annual exposure of the UK population from all natural and artificial sources is further evaluated in Watson *et al.* (2005).

Terrestrial gamma dose rates largely reflect the natural variation of potassium, uranium and thorium across the environment. The high spatial resolution airborne surveys, and their continuous local to regional scale, allow assessments of both the geological background and its spatial variability together with localised concentrations due to industrial/technological processes. The data sets provide a basis for studies of dose rates derived from both NORMs (naturally occurring radioactive materials) and TENORMs (technologically enhanced naturally occurring radioactive materials). Watson *et al.* (2005) discuss both subjects in relation to UK assessments.

Materials and methods

Estimates of radioelement concentrations are available from the Tellus airborne surveys and the ground geochemistry. The geochemical soil-sample estimates are referred to here as 'in-soil' and the airborne estimates as 'in-air'. The latter provide a measure of the air-absorbed dose rate directly above the ground surface. Radium (^{226}Ra) is the fifth daughter decay product of uranium (^{238}U) and is the parent of the natural gas radon (^{222}Rn), responsible for radon exposure of the population (i.e. at locations where radon gas may build up). An airborne radiometric survey includes measurements that are used to minimise the potential radon contributions in the air-column. When effective, the airborne data then provide estimates of the ground concentration of the radium–radon parent uranium. Airborne measurements of uranium levels can then be used as one of the supporting techniques in the estimation of indoor radon levels alongside indoor radon measurements and digital geological maps (Appleton *et al.*, 2008; Appleton and Hodgson, Chapter 20, this volume).

The present study considers air absorbed dose (AAD) defined, using the airborne ground concentration estimates (IAEA, 2010), as:

$$\mathbf{AAD\ (nGy\ h^{-1}) = 13.078 \times \%K + 5.675 \times eU + 2.494 \times eTh}$$

where radionuclide equivalent concentrations, eU and eTh, are in ppm. %K is percentage potassium. The combined dose measurement covers the energy range from 1.37 to

2.81 MeV and excludes contributions from artificial (man-made) sources. The airborne absorbed dose rate values may be converted into units of Bq kg^{-1} if comparison with international and UK legislation is required. A range of radionuclide conversion factors have been reported in the literature over the years and these are summarised by Beamish (2014).

Effective dose is a sum of multiples of equivalent doses in separate human organs each with a specific weighting factor. As noted in UNSCEAR (2000), to estimate annual *effective* doses, account must be taken of (a) the conversion coefficient from absorbed dose in air to effective dose and (b) the indoor–outdoor occupancy factor. The average numerical values of those parameters vary with the age of the population and the climate at the location considered. The UNSCEAR committee used 0.7 Sv Gy^{-1} for the conversion coefficient from absorbed dose in air to effective dose received by adult organs and 0.8 for the indoor occupancy factor, i.e. the fraction of time spent indoors and outdoors is 0.8 and 0.2, respectively. The annual effective dose rate (AEDR) in mSv y^{-1} may be calculated from the AAD rate using the above factors to give:

$$\textbf{AEDR (mSv y}^{-1}\textbf{) = AAD (nGy h}^{-1}\textbf{) * 8760 (h) * 1.0 * 0.7 (Sv Gy}^{-1}\textbf{) * 10}^{-6}$$

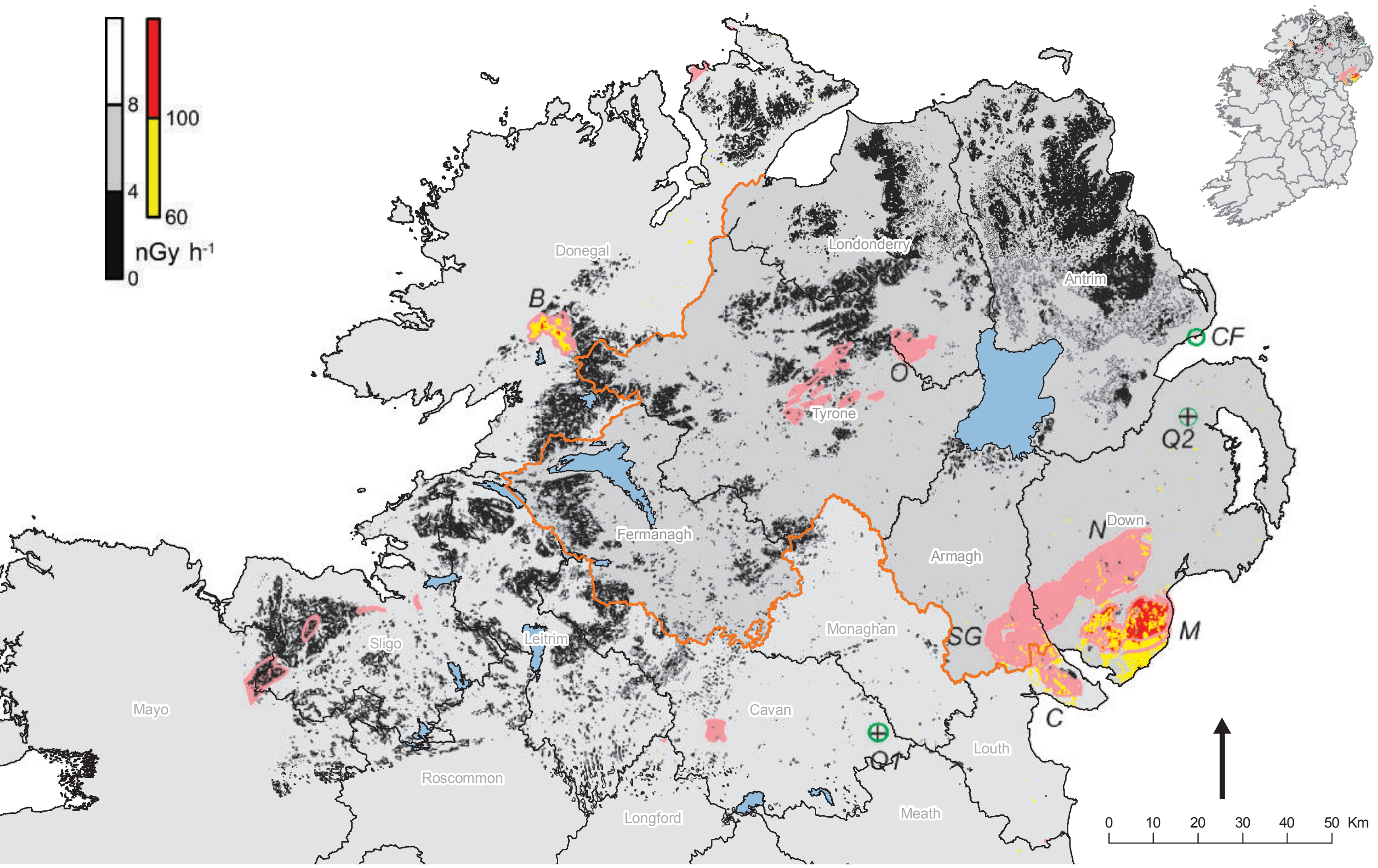
The factor of 8760 represents the number of hours (h) in a year and an occupancy of unity (meaning totally indoors) has been applied. The conversion indicates that the airborne dose rate values of 10, 100 and 1000 (nGy h^{-1}) produce equivalent annual effective dose estimates of 0.061, 0.61 and 6.1 mSv, respectively. The statutory UK limit on the amount of radiation to which the general public may be exposed, in excess of natural background and excluding medical exposure, is 1 mSv per annum (Watson *et al.*, 2005).

Results

Previous studies of dose rates across the UK noted the remarkable skew (to low values) of the original Tellus radiometric data set (Beamish, 2013). The composite Tellus radiometric data used here have had water bodies (areas > 5 km^2) removed. The unusually extensive areas of reduced radioactivity result from the attenuation of the signal by peat bogs, which cover some 17% of Northern Ireland (Beamish, 2013). However, when considering dose rates it is usually the high value end of the distribution that has most relevance to both NORM and TENORM investigations.

NORM contributions

Figure 18.1 summarises the low and high values of the observed distribution of dose rates obtained from the two Tellus surveys. The low values (<8 nGy h^{-1}) are shown in black–grey and the high values (>60 nGy h^{-1}) are shown in yellow–red. The widely distributed low values display a high spatial correspondence with areas of peat. At the scale shown, it is evident that high values are associated with a subset of the granite outcrops shown in pink.



The most spatially persistent set of high values are found in the eastern Mourne Mountains granite complex with other, less extensive zones being found within the Slieve Gullion, Carlingford and Newry granites. The Caledonian Barnesmore granite (B) in southern Donegal also displays a persistent zone of high values, largely confined to the western margins. The Ordovician granites (O) within the Midland Valley terrane are not associated with high values despite the absence of peat.

The maximum dose values within the data set occur in the eastern Mourne Mountains and range from 267 to 320 nGy h^{-1}; the precise value depends on factors applied with merging of the Tellus survey data sets. In order to assess the spatial behaviour of the dose rate values, it is useful to additionally consider soil and water information. Figure 18.2 shows an area centred on the outcrop of Mourne granite complex (the inner polygon in grey) with coloured contours of high dose rate (>150 nGy h^{-1}). Areas of peat are shown using transparent brown and water bodies are in blue. The high values are largely confined to the outcrop although it can be noted (Fig. 18.1) that values > 60 nGy h^{-1} extend to the south of the outcrop. The locations of the zones of high values are spatially complex and it is probable that the areas of extensive peat modify (attenuate) the flux pattern observed. It is worth noting that the granitic responses noted in Fig. 18.2 also have a concomitant elevated response in uranium values.

Figure 18.1. Air absorbed dose rate estimates obtained by the Tellus surveys. Low value amplitudes (<8 nGy h^{-1}) in grey scale, high amplitudes in yellow–red (>60 nGy h^{-1}). Pink areas are granite outcrops (B = Barnsmore, C = Carlingford, M = Mournes, N = Newry, O = Ordovician, SG = Slieve Gullion). Q1 and Q2 are locations of two quarries discussed in the text. CF = Carrickfergus.

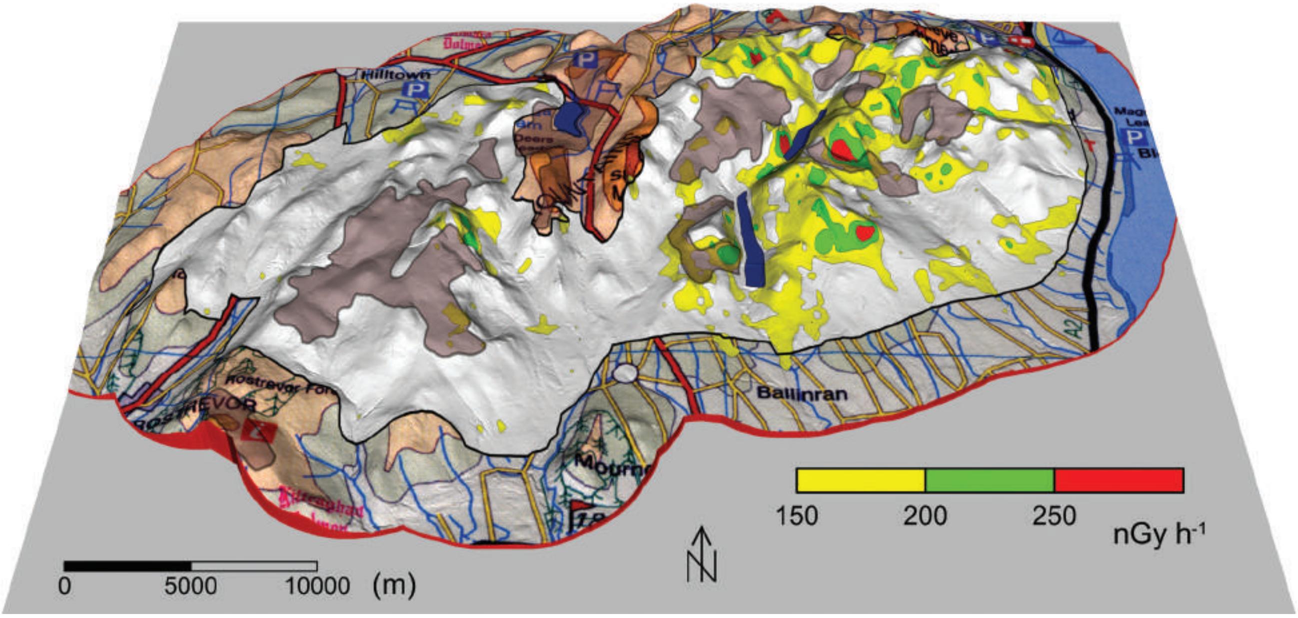


Figure 18.2. 3D perspective view (see north arrow) showing area of Mourne Mountains granite outcrop (in grey), with a 2 km extension showing base map, and draped on a base digital terrain model (DTM). Colour contours of high values of dose rate in yellow–green–red. Peat areas in brown, water bodies in blue.

The bedrock geology across the survey area is complex and any assessment of the radiometric response is complicated by the soil modification to the flux. The environmental component of annual dose rate is undoubtedly related to the main place of residence of each individual. It is possible to exploit the uniform coverage of the airborne survey data to provide estimates of city and town dose rates. When the complexities of the geological and soil responses are fixed (as would be expected at the housing-district scale), a more direct, population-related assessment can be undertaken. Given a spatial database of defined local authority areas, it is possible to conduct the analysis by size of population or by area; here we use the former. The analysis was conducted using areas with a population > 5000 individuals (2001 census).

Statistical analysis of the dose rates within 37 population centres of Northern Ireland is summarised in the box-whisker plot of Fig. 18.3, which is arranged in decreasing population size (from 276,705 to 5076). The majority of towns have dose rates below 50 nGy h^{-1}. Thirteen locations with higher dose rate levels are identified in red. These areas are predominantly underlain by granitic bedrock but there are additional contributions from the variable ground cover, so the method is effective in distinguishing the actual 'at-home' terrestrial gamma exposure levels experienced by the population. A similar analysis conducted using the Tellus Border data, where granitic areas are less extensive, revealed that the central values were all < 50 nGy h^{-1}. The high value tails of the distributions are also significant, since these reveal more localised high exposure values. The behaviour of the Carrickfergus distribution is very distinctive and is discussed further below.

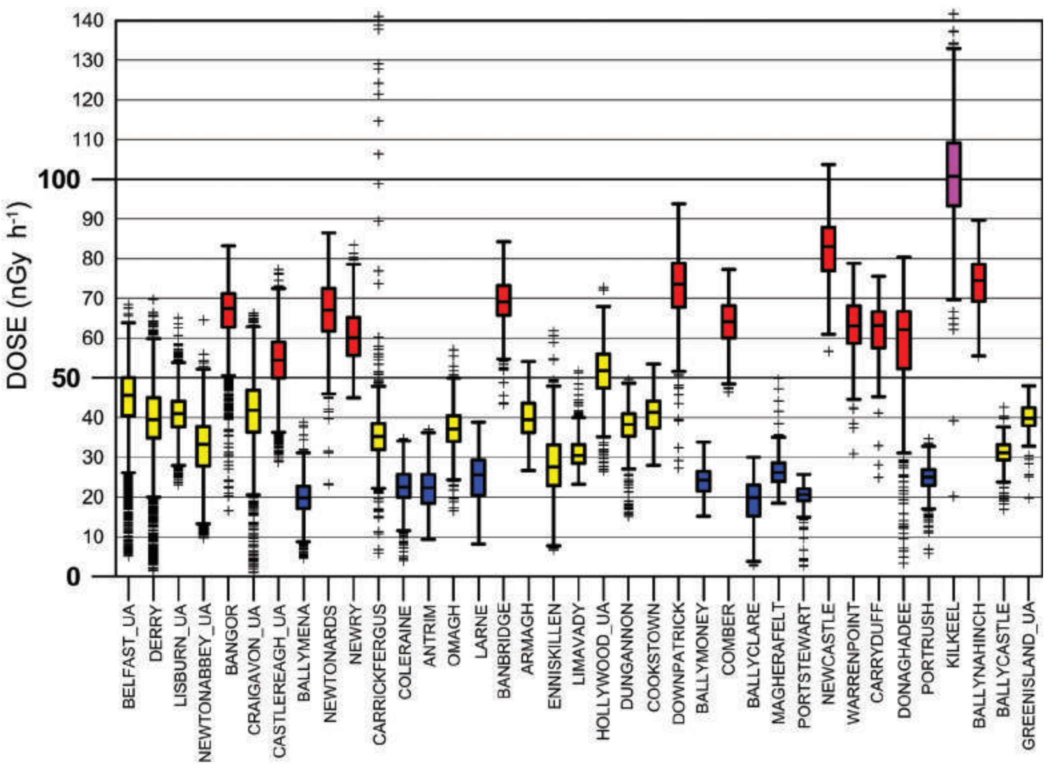


Figure 18.3. Box and whisker plot summarising the statistical behaviour of the airborne dose rate values classified according to the 37 towns of Northern Ireland with a population > 5000. Arranged in order of decreasing population.

TENORM contributions

The main central values for the Carrickfergus distribution (Fig. 18.3) lie in the range 30–40 nGy h^{-1}, but high values (data outliers) exceed this by a factor of 3. Kilroot Power Station, based in Carrickfergus, is Northern Ireland's largest power station. The waste material from combustion (fly ash) is contained within a landfill area on the coast. Figure 18.4 shows the detailed airborne observation points (dots) looking inland from the coast and centred on the landfill. High dose values are colour contoured and it is evident that the high values are confined to the landfill and that the data offer discrimination in the levels observed across the site. Further analysis, not shown here, indicates that the high levels are due to elevated concentrations in both thorium and uranium. In the context of other UK airborne data sets, colliery spoil heaps, iron ore mines and processing works and power stations are also marked by relatively high values of all three natural radioelements, but most notably thorium (Lahti and Jones, 2003). Radiometric measurements at ground level display a greater range of radionuclide concentrations due to the spatial averaging (typically > 100 × 100 m) inherent to the airborne measurement.

By their nature, TENORM contributions to high dose rates derive from existing and historical industrial activities and are spatially compact. A range of legacy effects due to many centuries of activity in the UK are reported by Beamish (2014). The largest recorded dose rate observed in modern UK airborne surveys is 579 nGy h^{-1}, from a highly localised

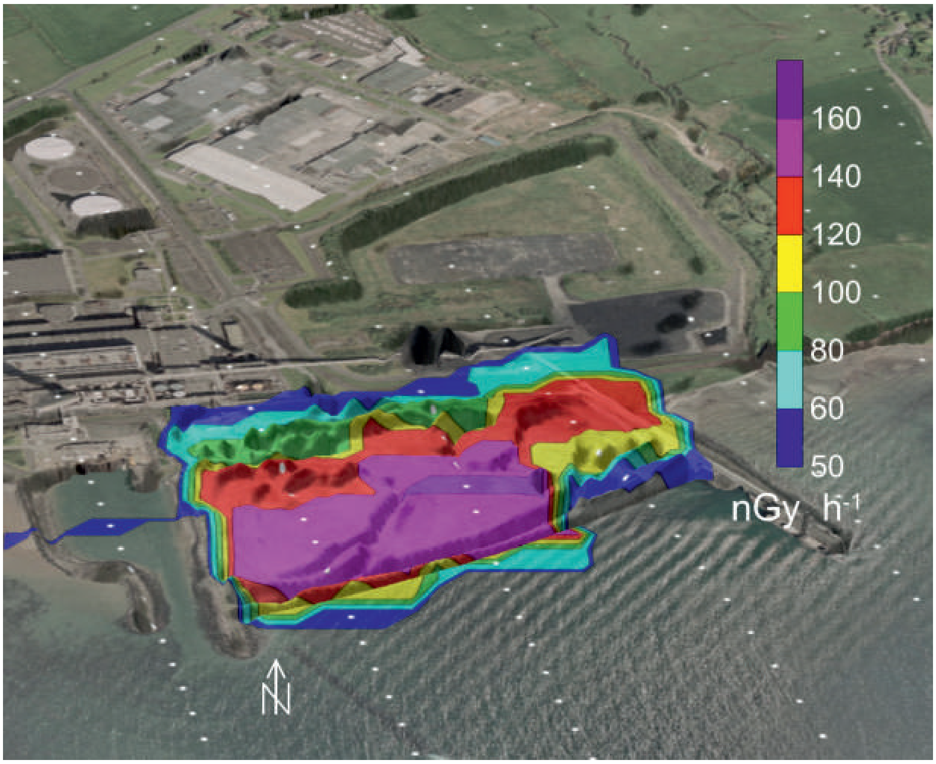


Figure 18.4. 3D perspective view (see north arrow), looking down on coastal landfill adjacent to the Kilroot power station at Carrickfergus. Air photograph draped on DTM. Colour contours show high values of dose rate. White dots are airborne survey sampling points, along flight lines every 200 m.

zone (predominantly along one flight line) associated with a former uranium mine in the vicinity of the St Austell granite in Cornwall. In the case of the Tellus surveys, TENORM contributions are observed to be typically less than 100 nGy h^{-1}. The relatively high value dose rates shown in Fig. 18.1 use a threshold of 60 nGy h^{-1}. The relatively high values account for only 1% of the total data. Areas of high dose were examined in relation to base topographical maps and airborne images. A significant proportion of the values occur in the vicinity of existing quarrying and other extractive industries. Two examples of localized detection (identified in Fig. 18.1) are shown in Fig. 18.5; both show the zone of values with dose rate > 60 nGy h^{-1}. Figure 18.5a shows a quarrying operation about 4 km SE of Stormont. The main zone is localised on one flight line. Figure 18.5b shows a larger quarrying operation in County Cavan, about midway between Bailieborough and Kingscourt, where two separate zones are detected across four flight lines. Site-specific conditions and potential causes of localised high values at a range of existing and former industrial sites across the UK are further discussed by Beamish (2014).

These determinations of TENORM are of course limited to the effects of direct radiation. They do not reflect the potentially greater health hazards of radiation from inhaled radioactive particulates (dust), which if lodged within the body may continue to emit tissue-damaging alpha and beta particles for many years.

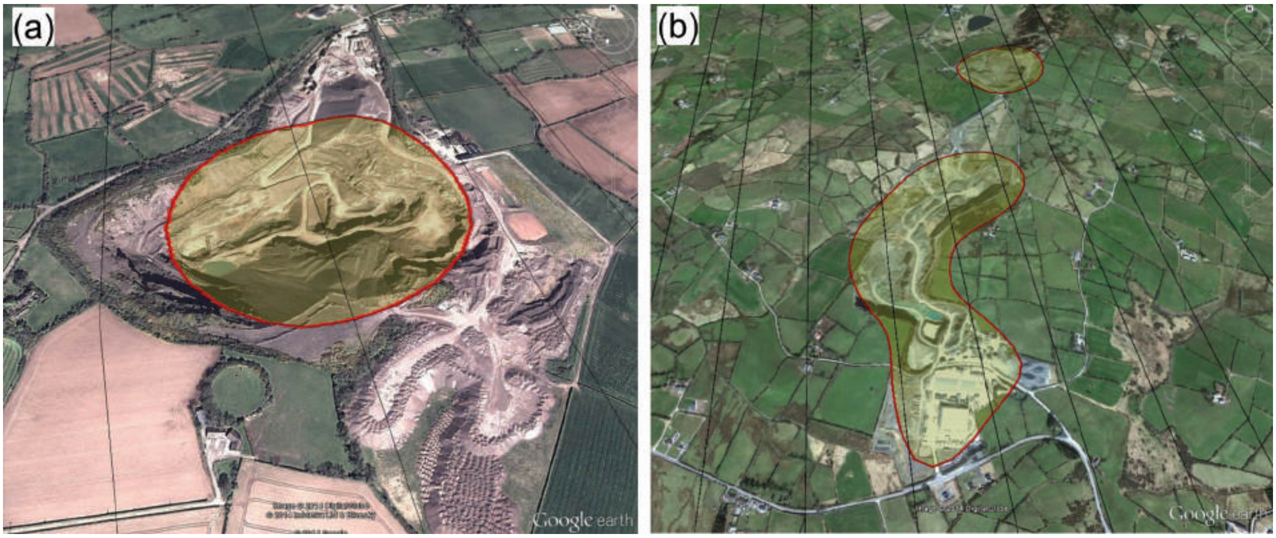


Figure 18.5. Two quarry areas with high (>60 nGy h^{-1}) dose rates identified with red contours and transparent infill. The black lines are flight lines (spaced at 200 m). Locations are shown in Fig 18.1. The background images are © Google Earth.

The Chernobyl nuclear accident took place in April 1986 and deposited significant amounts of the man-made radioelement caesium (^{137}Cs) over an extensive area of Europe. Although in the UK and Ireland this fallout was not directly hazardous to health, in some contaminated areas restrictions were placed on the movement and sale of sheep, which might accumulate caesium by grazing over an extended period.

Radiometric data from the first Tellus survey, alongside other airborne sets, were used to map the caesium (^{137}Cs) distribution (Scheib and Beamish, 2010; Rawlins *et al.*, 2011). The distribution obtained using the combined Tellus data sets is shown in Fig. 18.6, which identified zones and bands where high concentrations were deposited. The areas and bands of high concentration were found to cut across both and high and low topographical features, all soil types and differing land-use areas. The 'banding' in the results obtained was interpreted as representing a series of rain fronts intercepting the Chernobyl plume. Such a full understanding was, in fact, only achieved some 20 years after the accident.

Summary

Radiological assessments by bodies such as Public Health England (formerly the Health Protection Agency) and its predecessors have periodically refined assessments of the exposure of the population. The average annual dose from natural radiation remains at 2.23 mSv, with about half of this coming from indoor radon exposure. The average AAD UK dose rate, weighted by the distribution of population, has been found to be 32 nGy h^{-1}. It should be noted that, due to the spatial averaging inherent to the airborne measurements, ground distributions will typically display a higher spatial variance than the values reported here.

The pervasive blanket bog and organic soils, and their water content, attenuate the radioactive flux and therefore screen much of the survey area (say >25%) from potential

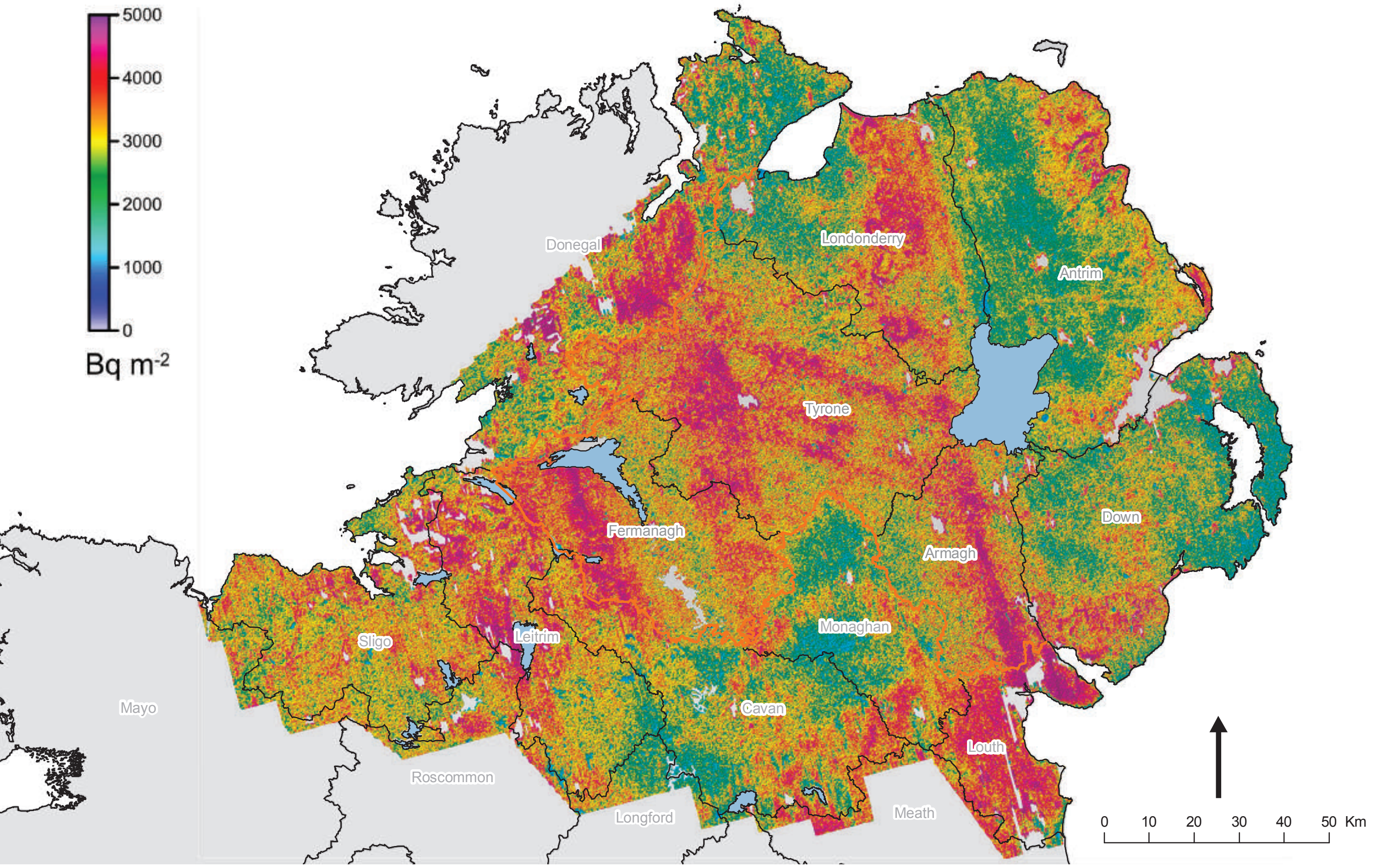


Figure 18.6. The caesium distribution obtained from the Tellus surveys (Bq m^{-2}). The distribution is cut to the coast and water bodies (>5 km^2), and high-fly areas (>180 m) are excluded.

high, in-air dose levels. The highest natural background dose rates are found in association with granites. Only a few small areas possess values in excess of 200 nGy h^{-1} (an effective annual dose rate of 1.23 mSv). The city–town analysis of dose rates, which covers the major percentage of the population, indicates that central values are routinely below 100 nGy h^{-1}, but one granite location (Kilkeel) has a median value close to 100 nGy h^{-1}.

TENORM contributions are localised and there are many contributions that can be identified, typically at levels below 100 nGy h^{-1}. The fly-ash landfill at Carrickfergus has a localised area providing in excess of 140 nGy h^{-1}.

The audit on environmental radioactivity reported here indicates that effective (biological) dose thresholds are within acceptable levels, subject to the inherent spatial averaging of the measurements.

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