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Gamma ray attenuation in the soils of Northern Ireland, with special reference to peat

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ABSTRACT

This study considers gamma ray attenuation in relation to the soils and bedrock of Northern Ireland using simple theory and data from a high resolution airborne survey. The bedrock is considered as a source of radiogenic material acting as parent to the soil. Attenuation in the near-surface is then controlled by water content in conjunction with the porosity and density of the soil cover. The Total Count radiometric data together with 1:250 k mapping of the soils and bedrock of Northern Ireland are used to perform statistical analyses emphasising the nature of the low count behaviour. Estimations of the bedrock response characteristics are improved by excluding areas covered by low count soils (organic/humic). Equally, estimations of soil response characteristics are improved by excluding areas underlain by low count bedrock (basalt). When the spatial characteristics of the soil-classified data are examined in detail, the low values form spatially-coherent zones (natural clusters) that can potentially be interpreted as areas of increased water content for each soil type. As predicted by theory, the highest attenuation factors are associated with the three organic soil types studied here. Peat, in particular, is remarkably skewed to low count behaviour in its radiometric response. Two detailed studies of blanket bogs reveal the extent to which peat may be mapped by its radiometric response while the intra-peat variations in the observed response may indicate areas of thin cover together with areas of increased water content.

1. Introduction

Airborne gamma spectrometer measurements form a significant component of the recent multi-parameter geophysical data sets acquired for exploration, environmental and baseline studies in the UK (Beamish and Young, 2009). The radiometric data have been used across a range of environmental assessments that include regional and local scale studies of natural and man-made distributions of excess concentrations (Lahti and Jones, 2003). The high spatial resolution data (200 m line spacing at ∼56 m elevation) have also been used in a number of soil-related studies. The uranium (U) data are now widely applied to radon mapping (Appleton et al., 2008, 2011). The use of data from multiple surveys allowed the distribution of caesium (^{137}Cs) across northern Britain to be studied in detail (Scheib and Beamish, 2010). Across the soils of eastern England, the study by Rawlins et al. (2007) indicated that the radiometric signals are useful for making thematic maps of soil and confirmed that a large proportion of the thorium (Th) and potassium (K) signals can be accounted for by parent material. Additionally, the airborne data (K signal) from Northern Ireland (NI) were used to study methods for improving current estimates of soil organic carbon (SOC) (Rawlins et al., 2009). The use of gamma ray attenuation (considered here) in conjunction with other airborne geophysical data (conductivity) was discussed in relation to the characterisation of wetland sites in North Wales by Beamish and Farr (2011).

Generally, environmental airborne radiometric studies employ one or more of the main, naturally occurring radioelement estimates (K, Th and U), together with their ratios, to establish relationships that have potential applications in areas such as soil mapping (e.g. Cook et al., 1996). Some baseline assessments of radiometric response as a function of bedrock (parent material) and/or soil type exist (Dickson and Scott, 1997; Beamish and White, 2011). Airborne studies differ from ground-based measurements in that the data are acquired uniformly and thus may encounter a range of water bodies including the sea. The attenuation of radiometric signal due to water or soil moisture is well-established (Carroll, 1981) and while studies of airborne data sets may note or discard unwanted attenuation features due to water or water-content, extensive studies of the radiometric signal attenuation

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levels in single baseline (meaning one-off) survey data sets are rare. Repeat (time-lapse) airborne radiometric surveys have the capability to provide assessments of snow-water equivalent (SWE) and/or soil moisture by estimation of the variation in attenuation, from a known calibrated baseline, due to varying water content (Carroll, 1987; Loijens, 1980). The ability to assess attenuation levels from one-off survey data is considered here. Ideally a baseline needs to be established in order to examine both enhanced and attenuated levels of radiometric signals. Usually the controlling factor when establishing radiometric signal levels would be that associated with the parent material. Each rock type, with an associated geochemistry, is assumed to contain a distribution of primordial radionuclides that were incorporated during the formation of the planet (IAEA, 2003).

When considering the amplitude of the radiometric response observed on, or above, the surface the simplest conceptual vertical model comprises two layers above bedrock. In the general case, the two upper layers would be defined by soil and superficial (Quaternary) deposits whose radiogenic content is assumed to be derived from the parent bedrock material. Whatever the near-surface material (i.e. the presence/absence and thicknesses of the 2 layers) the observed response will be derived from a given radiometric source concentration (assumed vertically uniform in the first instance) that is primarily obtained from a shallow subsurface zone (often <0.5 m). This zone is largely associated with soil cover and thus it is the properties of the soil that usually govern the radiometric decay (a standard exponential function) within a given material.

The majority of descriptions of gamma-ray attenuation found in the literature do not specifically include soils and soil properties. Radiometric attenuation in these materials is reviewed here and the existing theory is recast in more familiar terms of soil density, porosity and water saturation (in the absence of soil, other equivalent material properties will still apply). This allows two critical analyses of generic soils (i.e. type soils) to be developed. The first relates to the main depth interval that contributes to the observed response. The second analysis relates to the type-behaviour of uniform soils largely as a function of water saturation with density and porosity acting as secondary variables.

Here we use the NI survey data alongside two main 1:250,000 independent mappings of soil and bedrock to investigate levels of response attenuation. Secondary information on response enhancements is also obtained. Although, as part of the classification procedures, the behaviour of individual radioelements (K, Th and U) was obtained, the most useful summary attenuation measurement is the Total Count (TC) which, being a spectral summation, also offers enhanced signal/noise when examining low amplitude behaviour.

The classified TC data are coupled to variations in both intrinsic bedrock radiogenic concentrations and very-near surface (e.g. soil) material properties. No ground control measurements of general soil properties (particularly degree of water saturation, or soil moisture) are available at the 1:250,000 mapping scale used here. In order to extend the large-scale geostatistical analysis to the practical level, two case studies of attenuation behaviour across peat areas are considered. Peats, in particular, have a high sensitivity to soil moisture content. The first study considers the largest area of intact peat bog in Northern Ireland which is underlain by low response basalt bedrock. The second study area contains the second largest peat bog in Northern Ireland underlain by moderately radiogenic Carboniferous sandstones, limestones and mudstones. The case studies serve to demonstrate the manner in which the airborne soil classified radiometric data can provide a framework for further ground-based studies of soil moisture.

2. Theory

2.1. Gamma ray attenuation

The interaction of gamma rays with matter and the properties of airborne gamma-ray spectra are discussed by Minty (1967). The shape of the gamma-ray flux spectrum at airborne heights is a function of the concentration and geometry of the source radioelements, the thickness of any non-radioactive overburden, and the height of the detector above ground.

A common approach to the modelling of gamma-ray fields is a semi-empirical one based on monoenergetic (unscattered) radiation. The exponential absorption that characterises the passage of monochromatic electromagnetic radiation through a homogenous material is given by the Beer–Lambert Law (Davisson, 1965) as:

$$I = I_0 \exp(-\mu x) \tag{1}$$

Where I_0 is the initial radiation intensity. Intensity is usually described as a pulse count rate in photon detection systems. The linear attenuation coefficient (μ) of the material is an intrinsic property of each material and would usually be associated with a specific element of given atomic number. The mass attenuation coefficient (μ_m) of the material is given by:

$$\mu_m = \mu/\rho \tag{2}$$

where ρ is density. Equation (1) may then be expressed using the mass attenuation coefficient and the density of the material. Mass attenuation coefficients for air, water and concrete as a function of photon energy are tabulated by Minty (1967) across the energy range from 0.01 to 3 MeV. The attenuation coefficient is observed to decrease with increasing energy. At energies above 1 MeV, the half-thicknesses (thickness of material that reduces the intensity to half its initial value) range from 84 to 150 m (air), 9.8–17.5 cm (water) and 4.35–7.6 cm (concrete) (Grasty, 1979; Minty, 1967).

Løvborg (1984) discusses the general principles of gamma-ray attenuation and the effect of moisture content of materials. It is noted that Compton scattering (incoherent scattering) is the main significant attenuation interaction at the energies discussed here. In such circumstances the linear attenuation coefficient μ is proportional to the total number of electrons per unit volume of the material. Løvborg (1984) indicates that all elements with an atomic number less than 30 will have comparable mass attenuation coefficients. In the absence of water, soil, superficial and bedrock materials will have comparable attenuation coefficients at a given source concentration.

Hydrogen supplied to the material as absorbed or free water (e.g. pore water) then generates an additional attenuation provided by the additional electron content. Løvborg (1984) then establishes expressions for the gamma ray reduction from source material containing pore water. The expressions, discussed later, are based on the fact that water has 1.11 times as many electrons as most materials including soils (Grasty, 1997).

2.2. Soils

Soils are characterised as a three-phase system comprising solid, water and air. In the case of such mixtures it is necessary to replace the attenuation (decay) coefficients (μ) in equation (1) by a summation: $\Sigma_i \, \mu_i \, x_i$ where i enumerates the coefficients of each material (Endrestol, 1980). Rewriting equation (1) for a 3-phase soil gives:

$$I = I_0 \exp - (\mu_s \theta_s x + \mu_w \theta_w x + \mu_a \theta_a x) \tag{3}$$