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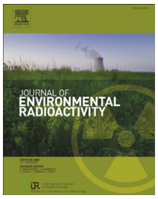

Geographically weighted regression and geostatistical techniques to construct the geogenic radon potential map of the Lazio region: A methodological proposal for the European Atlas of Natural Radiation

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A B S T R A C T

In many countries, assessment programmes are carried out to identify areas where people may be exposed to high radon levels. These programmes often involve detailed mapping, followed by spatial interpolation and extrapolation of the results based on the correlation of indoor radon values with other parameters (e.g., lithology, permeability and airborne total gamma radiation) to optimise the radon hazard maps at the municipal and/or regional scale. In the present work, Geographical Weighted Regression and geostatistics are used to estimate the Geogenic Radon Potential (GRP) of the Lazio Region, assuming that the radon risk only depends on the geological and environmental characteristics of the study area. A wide geodatabase has been organised including about 8000 samples of soil-gas radon, as well as other proxy variables, such as radium and uranium content of homogeneous geological units, rock permeability, and faults and topography often associated with radon production/migration in the shallow environment. All these data have been processed in a Geographic Information System (GIS) using geospatial analysis and geostatistics to produce base thematic maps in a 1000 m × 1000 m grid format. Global Ordinary Least Squared (OLS) regression and local Geographical Weighted Regression (GWR) have been applied and compared assuming that the relationships between radon activities and the environmental variables are not spatially stationary, but vary locally according to the GRP. The spatial regression model has been elaborated considering soil-gas radon concentrations as the response variable and developing proxy variables as predictors through the use of a training dataset. Then a validation procedure was used to predict soil-gas radon values using a test dataset. Finally, the predicted values were interpolated using the kriging algorithm to obtain the GRP map of the Lazio region. The map shows some high GRP areas corresponding to the volcanic terrains (central-northern sector of Lazio region) and to faulted and fractured carbonate rocks (central-southern and eastern sectors of the Lazio region). This typical local variability of autocorrelated phenomena can only be taken into account by using local methods for spatial data analysis. The constructed GRP map can be a useful tool to implement radon policies at both the national and local levels, providing critical data for land use and planning purposes.

1. Introduction

Indoor Air Quality (IAQ) in public and residential buildings has become a highly important environmental issue, especially in large, densely populated urban areas. Furthermore, the introduction of new building criteria, such as improved thermal insulation, compound this problem because they tend to reduce air exchange. On

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average people spend about 80–90% of their time in confined spaces (i.e. homes, workplaces, schools, etc.) and this percentage rises for children, the elderly, patients, etc. The monitoring of the healthiness of such environments is fundamental to reduce the exposure of the population to pollutants.

Natural radioactivity is the main source of human exposure to ionizing radiation. The inhalation of indoor radon (^{222}Rn) and its progenies contributes 50% of the annual dose of ionizing radiation. Whereas radon concentrations are extremely low in outdoor air, concentrations can become dangerously high indoors due to its accumulation in closed spaces. Sources for indoor radon include seepage from the surrounding soil and rock geology (so called "geogenic" radon), from the building materials used, or degassed from tap water having a groundwater origin. Accumulation, instead, is a function of ventilation within the building.

Radon is a gaseous trace element, chemically inert and ubiquitous in soil and groundwater. Radon is produced via the decay chain of primordial radionuclides ^{238}U, ^{232}Th and ^{235}U. The most abundant isotope is ^{222}Rn (from the decay chain of ^{238}U), which has a half-life of 3.82 days and decays itself to stable lead ^{206}Pb through an intermediate decay chain. Radon gas is colourless, tasteless, odourless and thus is not detected by the human senses even at high concentrations. Being a noble gas, radon is not very reactive, and is generally eliminated from the body. However, the real health hazards are its reactive, solid, daughters (i.e., ^{218}Po, ^{214}Po, ^{214}Pb, ^{214}Bi) which are also radioactive; a portion of the inhaled air will contain radon gas as well as their solid daughters, which bind to dust particles and irradiate lung and bronchial tissues as they decay.

Radon was classified as a human carcinogen in 1988 by the IARC (International Agency for Research on Cancer). More recently, the health effects linked to indoor radon exposure have been considered in the EC Directive 2013/59/EURATOM of 5/12/2013. It stated that recent epidemiological findings from residential studies demonstrate a statistically significant increase of lung cancer risk from prolonged exposure to indoor radon at levels above 100 Bq m^{-3}. It is estimated that about 9–15% of the approximately 14,000 annual cases of lung cancer in Europe can be attributed to radon and its progeny (Darby et al., 2005; Krewski et al., 2005; Charles, 2001; Kreienbrock et al., 2001; IARC, 1988). For this reason, indoor radon in public and residential buildings constitutes a significant environmental problem in urban areas (UNSCEAR, 2000; European Commission, 1990, 2013).

In general, it is accepted that areal variation of radon levels in houses primarily depends on the geological features of the investigated areas, because the bedrock and soil type constitute the main Rn sources, and because soil permeability controls Rn transport towards the surface (Bossew, 2015, 2014, 2013; Ciotoli et al., 2007; Shi et al., 2006; Friedmann, 2005; Kemski et al., 2005, 2001; Killip, 2005; Miles and Appleton, 2005; Apte et al., 1999; Gates and Gundersen, 1992).

Over the last few decades, various national indoor radon surveys have been performed in several European countries. These surveys, whose results are collected within the European Atlas of Natural Radiation by the European Joint Research Centre (Tollefsen et al., 2014; Dubois et al., 2010), often display their results as contoured "radon maps", and are considered as a preliminary risk assessment action. However, considering the lack of spatial correlation between houses having different structural characteristics and owner habits related to ventilation, this approach can be misleading. In some studies, the building-related variability (e.g., floor level, building materials, building type, presence of a basement, etc.) was recorded and filtered out to obtain, as far as possible, "true" radon indoor values. However, it is difficult to justify the interpolation of such data to predict the indoor radon levels of yet un-measured houses, or to cover unpopulated areas and draw conclusions about how to build new houses.

Another approach involves the assessment of the Geogenic Radon Potential (GRP) of a region, which is a quantity directly related to the local geology. A properly defined GRP based on a spatially continuous parameter might provide a reasonable guide for identifying radon-prone areas, particularly when the number and/or the quality of available indoor radon data is inadequate. The geological information by itself (e.g. lithological types, U and Ra content, soil-gas radon and permeability) may be sufficient to infer the radon potential. However, to date there is no generally accepted method of radon risk mapping.

The modelling approach proposed in this work uses different appropriate geospatial techniques, such as Geographical Weighted Regression (GWR), and geostatistics (kriging) to account for spatial autocorrelation and to produce a map of the Geogenic Radon Potential (GRP) of the Lazio region. Geological data and soil-gas data are provided by the Soil Protection and Remediation Department of the Regione Lazio and by the Fluid Chemistry Laboratory of the Earth Sciences Department, Rome University Sapienza, respectively. This wide database was elaborated in the GIS environment using ArcGIS 10.2 (Copyright © 1999–2013 Esri Inc.). All produced maps are constructed according to a grid format with having 1000 m × 1000 m unit cells created using vector to raster transformation, reclassification and interpolation of primary geological, geomorphological and geochemical data.

1.1. Radon in the shallow environment

The distribution of radon in soil-gas and, consequently the indoor activities, is strictly related to the geological characteristics of the studied territory (Kemski et al., 2009; Barnet et al., 2008; Ciotoli et al., 2007). Three main factors are known which predispose houses to elevated indoor radon levels. First, the regional and local geochemical and geological characteristics of the soil/rock will establish the in situ conditions. For example, uranium (^{238}U, ^{235}Th) and radium (^{226}Ra) content will control the amount of radon generated. Uranium and radium occur in all rocks at concentrations from 0.5 to 5 mg/kg, depending on the rock type. Igneous and metamorphic rocks (granites, acid lavas, tuffs, etc.) typically have very high uranium/radium contents and sedimentary rocks generally have lower contents (but high in some types like organic rich rocks, phosphates, reworked igneous or magmatic clastic rocks, etc.) (Drolet et al., 2013). Second, environmental conditions will control the rate of movement of soil radon toward the surface and into buildings. The escape of radon atoms at the grain scale is controlled by porosity, water content and grain-size, whereas migration toward the shallow environment is controlled by large scale geological features like rock thickness, permeability, fractures and karst (Castelluccio et al., 2012; Nazaroff, 1992; Etiope and Martinelli, 2002; Nazaroff et al., 1988; Tanner, 1980). Meteorological parameters like wind, barometric pressure, relative humidity and rainfall can also affect radon exhalation from the soil to the atmosphere (Piersanti et al., 2015; Szabó et al., 2013; Vasilyev and Zhukovsky, 2013; Zafrir et al., 2012; Baykut et al., 2010; Crockett et al., 2010; Fujiyoshi et al., 2006; Al-Shereideh et al., 2006; Winkler et al., 2001). Both these phenomena affect the GRP in terms of source and migration mechanisms. The third factor is the building characteristics that will influence radon entry and accumulation into buildings, such as gaps or fractures in the foundation that can provide gas entry pathways, particular building materials that can also be a source of radon production inside the building itself, and the ventilation habits of the building occupants (e.g. opening windows). Therefore, geology, quantified by a categorical classification system and or according to proxy variables (e.g., U/Ra

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