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Mapping geogenic radon potential by regression kriging

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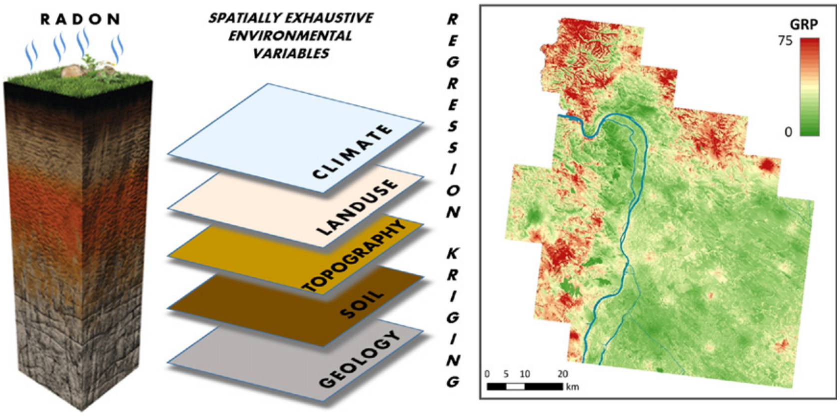
HIGHLIGHTS

- A new method, regression-kriging (RK) was tested for GRP mapping.
- Usage of spatially exhaustive, auxiliary data on soil, geology, topography, land use and climate.
- Inherent accuracy assessment (both global and local).
- Interval estimation for the spatial extension of the areas of GRP risk categories.
- Significance of fluvial sedimentary rock, pyroclast and land use properties on radon risk.

GRAPHICAL ABSTRACT



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ABSTRACT

Radon (^{222}Rn) gas is produced in the radioactive decay chain of uranium (^{238}U) which is an element that is naturally present in soils. Radon is transported mainly by diffusion and convection mechanisms through the soil depending mainly on the physical and meteorological parameters of the soil and can enter and accumulate in buildings. Health risks originating from indoor radon concentration can be attributed to natural factors and is characterized by geogenic radon potential (GRP). Identification of areas with high health risks require spatial modeling, that is, mapping of radon risk. In addition to geology and meteorology, physical soil properties play a significant role in the determination of GRP. In order to compile a reliable GRP map for a model area in Central-Hungary, spatial auxiliary information representing GRP forming environmental factors were taken into account to support the spatial inference of the locally measured GRP values. Since the number of measured sites was limited, efficient spatial prediction methodologies were searched for to construct a reliable map for a larger area. Regression kriging (RK) was applied for the interpolation using spatially exhaustive auxiliary data on soil, geology, topography, land use and climate. RK divides the spatial inference into two parts. Firstly, the deterministic component of the target variable is determined by a regression model. The residuals of the multiple linear regression analysis represent the spatially varying but dependent stochastic component, which are interpolated by kriging. The final map is the sum of the two component predictions. Overall accuracy of the map was tested by Leave-One-Out Cross-Validation. Furthermore the spatial reliability of the resultant map is also estimated by the calculation of the 90% prediction interval of the local prediction values. The applicability of the applied method as well as that of the map is discussed briefly.

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1. Introduction

Natural radon (^{222}Rn) is a radioactive noble gas occurring in every soil due to the radium (^{226}Ra) and uranium (^{238}U) content of the lithosphere. Since radon is an inert gas it can easily enter from the soil into buildings and its daughter isotopes can cause damage to lung tissue. This process produces more than half the average natural dose for humans (2.4 mSv y^{-1}) (UNSCEAR, 2008). The impact of radon on health is highlighted by EU data which state that about 20,000 people die every year in the EU (Darby et al., 2005) due to elevated indoor radon concentration. Radon concentration shows a wide distribution in the soil. In some areas as high as ten times the average readings can be measured.

In several countries a number of regulations were adopted and countrywide surveys were launched to identify radon prone areas (Gue, 2015). The idea of the geogenic map is to visualize the purely natural radon hazard, i.e. independently of anthropogenic factors which are subject to secular changes, as building styles and living habits change with time and also vary regionally, while the geogenic radon potential (GRP) is constant over geological eras (Bossew et al., 2013). The basic concept of a geogenic radon prone area is a region where for natural, i.e. geogenic reasons, elevated indoor radon levels and elevated probability of their occurrence must be expected (Bossew, 2014). The geogenic source of this hazard (or potential risk) at a location or over an area is described by its radon potential. Knowing the GRP of an area one can decide whether the area should be investigated in detail or the assessment of the site of new buildings is necessary.

There are a lot of methods to define and map the physical quantity geogenic radon potential (GRP) of an area. These methods are based on several measured parameters as numerical (such as permeability, radon concentration in soil air, and ^{226}Ra concentration) or geological, lithological data as categorical controls (Bossew et al., 2013). One of the internationally recognized approaches to quantify the GRP for the geogenic radon map of Europe is the continuous variable (formerly radon index) developed by Neznal et al. (2004), which is based on field measurements of the radon concentration in soil gas and the gas permeability of soils. This conventional continuous variable approach was applied for several areas of Hungary and the Czech Republic, too (Neznal et al., 2004; Szabó et al., 2014). In a different approach, multivariate classification, one cross-tabulates physical, mostly categorical factors which control the concept of the RP. The entries of the (possibly multi-dimensional) table are classified into RP classes. These factors are typically base and surface geology, geology, granulometry (as a proxy of permeability), hydrological properties, tectonics, and occurrence of “special features” such as caves, mines or other anthropogenically modified conditions which may enhance or reduce the natural RP. One elaborated example of this approach has been presented by Friedmann (2005).

At the same time several studies have shown the importance of the influence of soil physical parameters on the soil gas radon concentration. The effect of moisture content and grain size on radon emanation (radon escape from grain to the pore space) is well investigated with macroscopic soil models (Sakoda et al., 2010, Schumann and Gundersen, 1996). The emanation coefficient is higher where the moisture content is higher because the radon diffusion length is about 600 times lower (0.1 μm) in water than in air (63 μm) (Tanner, 1980). Thus radon atoms will remain in the pores (in the water) and could not reach another grain. Faheem and Matiullah (2008) investigated the moisture dependence of radon exhalation of several soils in laboratory measurements. Radon exhalation rate (radon escape from grain to the surface) was found to increase with an increase in moisture, reached its maximum value and then decreased with further increase in the water content. Schweikani et al. (1995) found that the increase in the moisture content causes a reduction in the radon diffusion since the pores through which radon diffuses is filled with water. Also they concluded that the degree of moisture saturation of the interstitial void space is the important factor rather than the moisture content as a percentage of the dry weight and/or the porosity of soil. The degree of moisture saturation is closely related to physical soil properties such as soil texture.

It is possible to establish accurate and robust estimation of specific derivatives by selected soil parameters using suitable pedo-radon transfer functions (PRTF). In this case more easily available soil maps and spatial databases can be used for the compilation of radon potential maps. Kemski et al. (2001) used an empirical ranking classification for the classification of geogenic radon potential due to the lack of exact functional relationship between radon concentration in soil gas and air permeability. Ielsch et al. (2002) emphasized the complicated interactions between the different pedological factors and radon exhalation, which preferably leads to statistically based models. Sun et al. (2004) found that radon exhalation from soil and soil radon concentration are more easily impacted by soil characters and they change in a rather large range. Winkler et al. (2001) investigated the spatial and temporal variability of the soil ^{222}Rn concentration at field scale for rather small pilot areas. They found significant differences in the case of various soil conditions. Oliver and Khayrat (2001) focused their investigation on the spatial variation of radon concentration in soil. They emphasized that appropriate information about the spatial scales of radon variation in soil is needed to effectively sample for its spatial prediction, that is, mapping. Buttafuoco et al. (2007) tested various geostatistical methods (ordinary kriging, lognormal kriging, ordinary multi-Gaussian kriging, and ordinary indicator cokriging) to study spatial structure of radon concentration for mapping purposes. The tested methods did not use environmental co-variables for the spatial inference. Multi-Gaussian kriging proved to be the most accurate method of the considered interpolation techniques.

Sampling based mapping is inherently predictive, the value or class of the mapped variable can only be estimated at unvisited locations (Gessler et al., 1995; Scull et al., 2003). Spatial prediction can be carried out (i) taking exclusively the mapped variable into consideration based on its spatial features; (ii) also based on the mapped variable, but the constraints of spatial validity are provided by further spatial, ancillary information; (iii) in every predicted location supported by environmental, auxiliary co-variables (McKenzie and Ryan, 1999).

Geology, climate, physical soil properties and radiological data are the main GRP forming environmental factors. Spatial exhaustive information on them is available relatively more easily. Thus spatial inference of locally measured GRP values can rely on methods which exploit their existence.

Regression Kriging (RK; Hengl, 2009) is a spatial prediction technique that combines the regression of the dependent variable on auxiliary variables with kriging of the regression residuals. It is mathematically equivalent to the interpolation method variously called universal kriging and kriging with external drift. (Hengl et al., 2004). Essentially, RK respects this fact, neither environmental correlation nor pure geostatistical interpolation (simple, ordinary kriging) alone is able to account for the whole spatial variation that is to produce approximately perfect map products. They can be used as complementary spatial inference approaches where one can improve the other's drawbacks.

The main objective of the study has been to test a new method of GRP spatial prediction provided by regression-kriging (RK) using spatially exhaustive auxiliary environmental variables (geology, soil physical properties, topography, land use and climate). The expected result has been a more detailed map than previous maps based on spatial resolution of the selected auxiliary variables. A further aim has been to determine the performance and uncertainty of the method.

2. Materials and methods

2.1. Study area

The study area is located in the Pannonian Basin, in Central Hungary and includes Budapest, the majority of Pest County and some surrounding