Journal of Environmental Radioactivity 129 (2014) 107–120

Contents lists available at ScienceDirect

Journal of Environmental Radioactivity

journal homepage: www.elsevier.com/locate/jenvrad

Mapping the geogenic radon potential: methodology and spatial analysis for central Hungary

Katalin Zsuzsanna Szabó [a], Gyozo Jordan [b], Ákos Horváth [c], Csaba Szabó [a,*]

[a] Lithosphere Fluid Research Laboratory, Department of Petrology and Geochemistry, Eötvös University, Pázmány Péter sétány 1/C, 1117 Budapest, Hungary
[b] Institute for Geological and Geochemical Research, Research Centre for Astronomy and Earth Sciences, Hungarian Academy of Sciences, Budaörsi út 45, 1112 Budapest, Hungary
[c] Department of Atomic Physics, Eötvös University, Pázmány Péter sétány 1/A, 1117 Budapest, Hungary

ARTICLE INFO

Article history:
Received 23 August 2013
Received in revised form
2 December 2013
Accepted 12 December 2013
Available online 9 January 2014

Keywords:
Hungarian geogenic radon potential
Soil gas radon
Soil gas permeability
Spatial modeling

ABSTRACT

A detailed geogenic radon potential (GRP) mapping based on field soil gas radon and soil gas permeability measurements was carried out in this study. A conventional continuous variable approach was used in this study for GRP determination and to test its applicability to the selected area of Hungary. Spatial pattern of soil gas radon concentration, soil permeability and GRP and the relationship between geological formations and these parameters were studied by performing detailed spatial analysis.

Exploratory data analysis revealed that higher soil gas radon activity concentration and GRP characterizes the mountains and hills than the plains. The highest values were found in the proluvial–deluvial sediments, rock debris on the downhill slopes eroded from hills. Among the Quaternary sediments, which characterize the study area, the fluvial sediment has the highest values, which are also located in the hilly areas. The lowest values were found in the plain areas covered by drift sand, fluvioeolic sand, fluvial sand and loess. As a conclusion, radon is related to the sediment cycle in the study area.

A geogenic radon risk map was created, which assists human health risk assessment and risk reduction since it indicates the potential of the source of indoor radon. The map shows that low and medium geogenic radon potential characterizes the study area in central Hungary. High risk occurs only locally. The results reveal that Quaternary sediments are inhomogeneous from a radon point of view, fluvial sediment has medium GRP, whereas the other rock formations such as drift sand, fluioeolic sand, fluvial sand and loess, found in the study area, have low GRP.

1. Introduction

The adverse health effects of radon are well documented (e.g. WHO, 2009). Regulation and mitigation is therefore envisaged which among other measures requires knowing the geographical extent of the hazard related to radon. The radon risk is often defined as the probability that indoor radon exceeds a risk; the geogenic source of the hazard (or potential risk) at a location or over an area is described by its radon potential.

Knowledge on the radon potential of an area can support decisions on whether further local measurements are necessary in the areas of planned development. Factors influencing indoor radon concentration are living habits such as ventilation and building structure, including building material or presence and type of basement and cellar below the house. The geogenic radon potential (GRP) shows the potential of the source of indoor radon 'what the Earth delivers' because generally the subsurface (soil gas radon concentration) is the main source for indoor radon concentration (UNSCEAR, 2000). The GRP is independent from the influence of any building related or living habit factors. Besides this, the relationship between soil gas radon concentration and indoor radon concentration is well known (Appleton and Miles, 2010; Barnet et al., 2005; Barnet, 2011; Barnet and Pacherová, 2010; Chen et al., 2009; Kemski et al., 2005).

In 2008 the Radioactivity Environmental Monitoring (REM) group at the Institute for Transuranium Elements (ITU), Joint Research Centre (JRC) decided to compile a geogenic radon map of Europe in the frame of preparing a European Natural Radiation Atlas (De Cort, 2010). In contrast to the indoor radon map of Europe that covers only areas where indoor measurements are available, the geogenic map will present the radon potential at any location in Europe using geological, soil data and soil gas radon measurements (De Cort, 2010). However, several definitions of a quantity "radon

* Corresponding author. Tel.: +36 1 372 2500x8338; fax: +36 1 361 2212.
E-mail addresses: sz_k_zs@yahoo.de (K.Z. Szabó), gyozojordan@gmail.com (G. Jordan), akos@ludens.elte.hu (Á. Horváth), cszabo@elte.hu, cszaboo@yahoo.com (C. Szabó).

0265-931X/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jenvrad.2013.12.009

potential" exist in the literature (Alonso et al., 2010; Barnet et al., 2005; Barnet and Fojtíková, 2008; Barnet and Pacherová, 2010; Chen, 2009; Chen et al., 2012; Neznal et al., 2004; Dehandschutter and Ciotolli, 2010; Friedmann, 2005; Guida et al., 2010; Ielsch et al., 2010; Kemski et al., 2001; Miles et al., 1991; Miles and Appleton, 2005; Tóth et al., 2006; Schumann, 1993), which sometimes causes confusion. One suggested approach to quantify the geogenic radon potential for the geogenic radon map of Europe is the continuous variable (formerly radon index) developed by Neznal et al. (2004) (Eq. (1)):

$$\mathrm{GRP} = \frac{c_\infty}{-\log_{10} k - 10} \qquad (1)$$

where c_∞ is the equilibrium soil gas radon activity concentration at a definite depth (0.8–1 m) (kBq m^{-3}) and k is the soil gas permeability (m^2). Based on many years of extensive research in the Czech Republic, three categories of GRP (Eq. (1)) were set: low (GRP < 10), medium ($10 <$ GRP < 35) and high ($35 <$ GRP) (Neznal et al., 2004). The geogenic radon potential of Neznal et al. (2004) is based on the radon index classification table formerly used in the Czech Republic (Barnet, 1994).

In many cases soil gas radon concentration is subject to temporal variation and the seasonal variation is mostly higher than the diurnal one (Al-Shereideh et al., 2006; Barbosa et al., 2007; Baykut et al., 2010; Crockett et al., 2010; Dubois, 2005; Neznal et al., 1995; Neznal and Pernička, 1996; Neznal and Neznal, 2006; Perrier et al., 2009; Smetanová et al., 2010; Sundal et al., 2008; Szabó et al., 2013; Winkler et al., 2001). Seasonal variation of soil gas radon concentration can have great impact on the value of c_∞ in case of a single local point measurement, and therefore on its representativeness for the location.

In Hungary, several indoor radon surveys were performed in the last decades and indoor radon potential maps have been made (Hámori et al., 2006a,b). Strong dependence of indoor radon measured at one-storied houses with no basement on the geological background was demonstrated (Minda et al., 2009). Soil gas radon measurements were also performed by several institutes and universities for research purposes, such as during the rehabilitation processes in the area of the closed uranium mine (Mecsek Mts, SW-Hungary) (Somlai et al., 2006). However, geogenic radon potential mapping has not been performed in Hungary yet.

The main aim of this study is to present a detailed GRP mapping based on soil gas radon and soil gas permeability measurements and to create a radon risk map that helps regional planning. In this study, the continuous variable approach (Eq. (1)) was used for GRP determination. A further objective is to characterize geological formations with radon, soil gas permeability and geogenic radon potential based on field measurement results. In addition, a detailed spatial analysis using local trend analysis, variogram and autocorrelation analysis and regression analysis were carried out to reveal and numerically describe spatial patterns in the three parameters (radon concentration, soil gas permeability and geogenic radon potential). The specific objective was to develop a GRP map for the studied region including Hungary's capital city Budapest and surrounding area, in order to assist human health risk assessment and risk reduction.

2. Study area

The study area is located in the Pannonian Basin and includes Budapest, the majority of Pest County (PC), the westernmost part of Nógrád County (NC) and some areas from other adjacent counties (Komárom-Esztregom County: KC, Fejér County: FC) (Fig. 1). The 80 × 90 km highest extension of study area encompasses 5400 km^2 covering 6.5% of the country. This part of Hungary has the highest

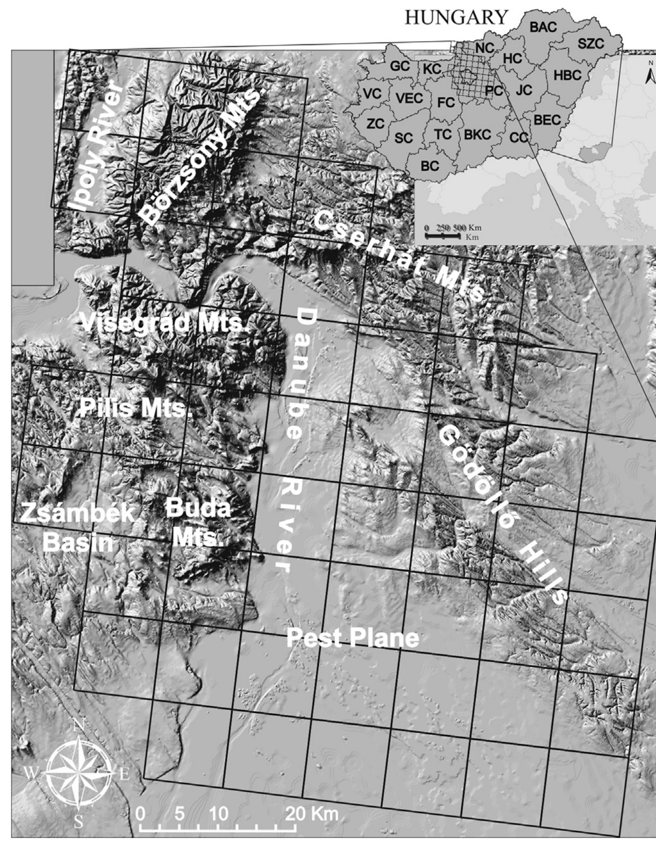

Fig. 1. Shaded relief map of the study area showing joining point of the two highest Hungarian mountain ranges, the North Hungarian Mountains and the Transdanubian Mountains with the Great Hungarian Plane on either side of River Danube. Inset: location of the studied Pest County and some of the neighboring counties. FC – Fejér County, KC – Komárom-Esztergom County, NC – Nógrád County, PC – Pest County.

population density: 28% (2.83 million) of the population of the country (9.9 million) live in the 220 settlements of the study area. The area is also characterized by diverse geological background, thus providing excellent conditions for radon risk mapping and geological modeling research.

The diverse geological background can be related to the joining point of the two highest Hungarian mountain ranges, the North Hungarian Mountains and the Transdanubian Mountains with the Great Hungarian Plane. Accordingly, there are hills (the highest elevation is 938 m asl.) along the longitudinal extension (N–S direction) in the western part of the area. The Danube River enters the study area from west and sharply turns to the south at the Danube Bend, an intense touristic area. The Northeast part is hilly (Cserhát Mts. and Gödöllő Hills with the highest elevation 652 and 345 m asl., respectively). Northwestern part of the Great Hungarian Plane, the Pest plane covers the middle and southern parts (100–150 m asl.) of the study area (Fig. 1).

The northernmost part of the study area comprises the Miocene volcanic andesite and dacite areas of the Visegrád Mts. and Börzsöny Mts. over the Tertiary sedimentary basin covering the Paleozoic crystalline basement. Along the Ipoly River, a Holocene alluvial plain (mud and sand) is found. On the Mesozoic carbonates formation Eocene and Oligocene limestone, marl and sandstone evolved in the Pilis Mts., whereas Triassic limestone, dolomite and marl build up the Budai Mts. In the foreground of the Budai Mts. lays the Zsámbék Basin. It consists of Pliocene clay, sand, gravel in the western part, Miocene clay and limestone in the middle and eastern part and Pleistocene loess in the southern part. The Mesozoic and Paleozoic strata of the Pest Plane and Gödöllő Hills is covered by several