Ground radon spatio-temporal variability evaluation

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Abstract

Ground radon is one of the main sources of natural radiation contributing to the population irradiation by more than forty percent. Due to this fact, a strong emphasize is laid on the bedrock radon potential evaluation and on the radon risk mapping. In spite of the fact that these areas are being a focus of researches for a long time, there are several issues of ground radon spatio-temporal behaviour that had hitherto passed unnoticed. These are for example ground radon short and middle term unstable nature or its dependence on various environmental variables. This paper is a contribution to this problematic. The purpose was to analyse ground radon spatio-temporal variability in order to determine typical features of its behaviour and to point out respective practical consequences. To do so, 49 randomly distributed stable probes were established and 35 repeated measurements, with delay ranging from two to five days were carried out. This gave 49 time series, each consisting of approximately 35 observations. Firstly, summary characteristics describing respective time series as a whole were derived. This was mainly time series dynamics expressed by chosen acceleration index. This measure was consequently put into the space and "the spatial variability of temporal variability" was evaluated. As far as spatial analyses, the trend component of theses values extracted by Trend Surface Analyses was analysed and preliminary interpretations were proposed. Secondly, these data were spatially interpolated and resultant model was classified according to chosen classification scheme. In this point, the geostatistical tools were employed to determine the character of spatial dependence and to derive continuous model of ground radon temporal variability. This information allows analysing how ground radon temporal behaviour relates to environmental variables such as soil and bedrock, relief morphometry, microclimate characteristics, etc.
In this study we affirmed and quantified by the experiment high ground radon temporal variability, and we determined the character spatial autocorrelation of individual time series summary characteristics. The casual aspect of this behaviour is the subject of further research. Respective analyses were accomplished in the IDRISI32, ISATIS and STATISTICA environments.

Abstrakt

Pôdny radón je jeden z dominantných zdrojov prirodzenej rádioaktivity, ktorý prispieva k celkovému ožiareniu populácie viac ako štyridsiatimi percentami. Z tohoto dôvodu je významná pozornosť kladená na monitoring radónového rizika a na mapovanie radónového potenciálu geologického podložia. Aj napriek skutočnosti, že tieto oblasti sú už po dlhú dobu oblasťou výskumu, v oblasti časovo-priestorového správania pôdneho radónu stále existuje množstvo nezodpovedaných otázok. Sú to najmä jeho krátko a strednodobo časovo nestabilný charakter, alebo závislosť na množstve environmentálnych premenných.

Táto štúdia je príspevkom k tejto problematike. Cieľom je analyzovať niektoré prvky časovo-priestorovej variability pôdneho radónu a vyvodiť príslušné praktické implikácie. Pre získanie zdrojových údajov bolo založených 49 stabilných odberových miest a na každej z nich bolo realizovaných 35 opakovaných meraní s odstupom 2-5 dní. Prvým cieľom bolo získať sumárne charakteristiky popisujúce jednotlivé časové série ako celky, pričom bol použitý vybraný index zrýchlenia časového radu. Tieto údaje boli následne vztiahnuté k svojej priestorovej polohe a bola hodnotená „priestorová variabilita časovej variability“. V rámci priestorových analýz bol metódou trendového povrchu extrahovaný trendový komponent týchto hodnôt a boli vyvodené príslušné interpretácie. V druhej časti bolo analyzované územie klasifikované do kategórií s podobným charakterom časového správania. Uvedené vstupné údaje boli interpolované a výsledný model bol klasifikovaný využitím vhodnej klasifikačnej schémy. V tomto kroku boli využité vybrané geoštatistické nástroje, pomocou ktorých bol určený charakter priestorovej autokorelácie odvodených časových charakteristík a bol odhadnutý spojitý model vyjadrujúci časovú variabilitu pôdneho radónu. Tieto informácie ďalej umožňujú efektívne hodnotiť závislosť časovej variability pôdneho radónu na premenných ako pôdy a geologické podložie, terénna morfometria, mikroklimatické charakteristiky a pod.

V rámci štúdie bola experimentom potvrdená vysoká časová variabilita objemovej aktivity pôdneho radónu a zistená miera priestorovej autokorelácie jednotlivých sumárnych charakteristík časových radov vztiahnutých ku svojej priestorovej polohe potvrdzuje prítomnosť priestorových zákonov formujúcich tento jav. Kauzálny aspekt tohto správania je oblasťou ďalšieho výskumu. Jednotlivé analýzy boli realizované v prostredí IDRISI 32, ISATIS a STATISTICA.

Introduction

Radon and its daughter products can be found in almost any place in the environment. The main sources of those present indoor are the bedrock and soils, thus a great deal of monitoring activities focus just on these variables. Besides, there are a lot of other factors affecting its volume activity and ability of being released, such as relief morphometry, ground water occurrences, or weather conditions the exact effect of which still remain unexplained. This is a contribution to this problematic following the works by Hlásny et al. (2003), Ďurec et al. (2003) and Hlásny and Ďurec (2004). Other works on the ground radon spatio-temporal analyses are those by Húlka et al. (1994), Oliver and Kharayat (1999), Reimer (1995), and others.

There are several works proving ground radon short and middle term temporal variability, while over longer periods it remains relatively constant. This depends mainly on weather condition, especially air pressure, and related wetness of the soil horizon. Its long-term constancy relates, logically, to the invariant both bedrock, as its main source, and the soil conditions affecting its ability of being released.

The knowledge of ground radon temporally instable nature is an important indicator of the uncertainty when classifying areas under investigation into the radon potential categories, or if trying to predict radon volume activities at unrecorded locations inclusive this information. As proved in the work by Hlásny and Ďurec (2004), the uncertainty in the positions of individual radon potential/risk zones might have serious practical implications. Methodologically, this issue touches the processing of all the temporally unstable phenomena.

The purposes

The purpose of this study is to analyse ground radon spatio-temporal variability in order to determine typical features of its behaviour and to point out respective practical consequences. To do so, 49 randomly distributed stable probes were established and 35 repeated measurements, with delay ranging from two to five days were carried out. This gave 49 time series, each consisting of approximately 35 observations. Firstly, summary characteristics describing respective time series as a whole will be derived. This is mainly time series dynamics expressed by chosen acceleration index. This will be consequently put into the space and "the spatial variability of temporal variability" will be evaluated. As far as spatial analyses, the trend component of theses values extracted by Trend Surface Analyses will be analysed and preliminary interpretations will be proposed. Secondly, the spatial interpolation will be employed to derive a continuous model. This will be classified according to chosen classification scheme. In this point, the geostatistical tools will be employed to determine the character of spatial dependence and to derive continuous model of ground radon temporal variability. This information allows analysing how ground radon temporal behaviour relates to environmental variables such as soil and bedrock, relief morphometry, microclimate characteristics, etc. Respective analyses will be accomplished in the IDRISI32, ISATIS and STATISTICA environments.

Radon – An overview

Three radon isotopes occur in the environment - ^{222}Rn, ^{220}Rn a ^{219}Rn. Just ^{222}R isotope contributes to the man's irradiation in the most important manner. Its half-life is 3,5 day, what is sufficiently long time to spread over significant distances from the place of its origination. (Šáro & Tolgyessy 1985, Vlček 1991). Mainly closed areas such as houses, caves and mines exhibit increased radon volume activities. Just the concentration in houses is a critical indicator of measures adopted to protect people from unwanted irradiation. According to UNSCEAR (1988), average volume activity of the ^{222}Rn isotope is ranging among individual countries from 10 to 100 Bq.m^{-3} and the world average is 40 Bq.m^{-3}.

The main sources of indoor radon are:

- the bedrock and soil. Ground radon concentration depends on radon Ra^{226}occurence, the radioactive decay of which produces gas radon. The amount of radon released depends on soil and rocks physical properties. The radon coming from these sources can pass to the buildings through unisolated flooring, cracks in house bases, sewerage, drainage, etc.
- building materials of walls and floors. These are the materials with varying amount of Ra^{226}. Just their crashing and milling in factories might caused increased radon release.
- potable water is further, in general less important contributor. It might be contaminated in the lower parts of the bedrock (according to Nikodemová 1995).

At present, these facts are reflected by relevant legislative, worldwide. In the Slovak Republic this is mainly the law NR SR No. 272/1994 Z.z. „on the men's health protection“ and Slovak Ministry of Health directive No. 12/2001 Z.z. „on the requirements on radiation protection assurance“. This directive also defines exact values the surpassing of which requires measures adoption treating radon permeations into the buildings. In the world, this field is covered by *UNSCEAR – United Nations Scientific Committee on the Effects of Atomic Radiation* and *ICRP – International Commission on Radiological Protection*.

The methods

Field data gathering

Ground radon samples were extracted by means plastic syringe from the iron pipe hammered into the depth of 80 cm. These were transported to the laboratory in Lucas cells and evaluated by means of LUC instrument. The probes had been remaining in their positions during the all experiment. The sampling design was proposed by random positions generator (Fig. 1). In order to localize the positions wanted effectively, a topographic map and aerial photo with highlighted and numbered probes locations were used. In order to precise individual sampling points positions, these were measured by GPS Magellan ProMark X with submeter accuracy. Due to ground radon temporally instable nature this appears sufficient.

Spatio-temporal analyses

Field data gathering gave a great number of numerical data arranged in 49 time series. Two groups of methods were used to analyse ground radon spatio-temporal variability. The first one, belonging to standard statistical methods, was used to derive basic descriptive statistics of both individual time series and radon field as a whole. Besides, specialised procedures for time series analyses were used – the computation of first and second differences, coefficient of acceleration, rate of increment, increment index, etc. according to Brabenec (1977) and Bakytová et al. (1979).

In particular, to characterize ground radon temporal dynamics, we used first differences computed as the difference of two consequent values of the series, as

$$\Delta\, y_i = y_i - y_{i-1}$$

that express absolute increase or decrease of quantity measured during the period $\Delta\, t$. Consequently the absolute acceleration was computed as the difference of two consequent first differences

$$\Delta\, (\Delta\, y)_i = \Delta\, y_i - \Delta\, y_{i-1}.$$

These are to express absolute acceleration, i.e. how large, and whether positive or negative was the next increment/decrement different from the previous one (Šmelko, 1998). As summary characteristic for each time series, the average of second differences – so called coefficient of acceleration – was computed. This is a key quantity for further analyses.

Second group of analytical methods used belongs to those of spatial statistics and geostatistics facilitated by means of GIS. These were used to put the results of numericaly carried analyses into the space and to analyse radon field temporal dynamics spatially. Firstly, the trend component of derived sumarry characteristic was extracted. This is to show, in highly generalized form, the main spatial trends of radon field temporal behavior. This might be analytically expressed by a polynomial function of certain degree. A general term according to Ripley (1981) is as follows:

$$f(x, y) = \sum_{r+s<p} a_{rs} x^r y^s \quad \text{which is used to minimize} \quad \sum_{1}^{N} \{z(x_i) - f(x_i)\}^2$$

where p expresses the order of the polynomial, $z(x_i)$ are available data points, r and s are respective coefficients.

To extend this concept the spatial interpolation was used to design a continuous spatial model of ground radon temporal variability. To do so, the ordinary kriging according to Matheron (1971), Wackernagel (1998), or Isaaks and Srivastava (1989) was used. The information on spatial autocorrelation was also derived and interpreted. To classify the research area into the categories by similar features of temporal behaviour, the coefficients of accelerations were numerically classified into four categories, the threshold values of which were derived from the histogram by reading more remarkable changes of its shape (according to Burrough, 1986).

Case study

Research area

Research area spreads in the eastern part of the Kremnické vrchy Mountain, in the Malachovské predhorie and Jastrabská vrchovina area. In the south, the area is bordered by the Turovské predhorie and in the west by the Flochotský chrbat area (Fig. 1). The area was chosen due to its relatively homogenous geology structure in order to reach ground radon stationary behaviour within the spatial domain considered. The extent of the area is approximately 3x3 km. Its geological background is composed of *Mesozoic carbonate rocks*, which are covered by *Tertiary sediments* and *volcanic rocks*. The higher radon concentration can be preliminary expected due to the andesitic volcanoclastics, but might be complicated by two factors – assumed NE-SSW and NW-SE fault systems and possible presence of underlying *Permian sedimentary rocks.* The position of the area in the vicinity of Banská Bystrica city allows field works to be accomplished within the acceptable time and cost limits.

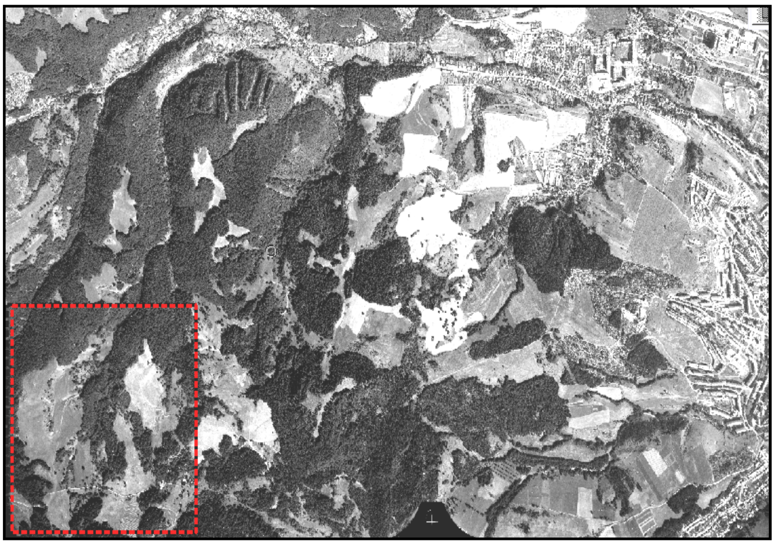

Fig. 1. Research area position in relation to Banska Bystrica city (Central Slovakia). In the right side can be seen the border of the Banska Bystrica city built up area.

Source data and sampling design

In the Fig. 2 can be seen research area aerial photo and distribution of 49 stable probes. Random sampling was used instead of systematic one, used in ground radon monitoring obviously, to facilitate respective geostatistical analyses. Besides, the use of systematic sampling threatens with potential correspondence with geology structure that influences ground radon spatial distribution substantially. Since field measurements required soil profile to be dry, this was scheduled to summer months (July-October, 2003). Preliminary, it was proposed to do repeated measurements by each three days, but due to the weather condition, and also a human factor, this could not be kept. Some of probes were destroyed during the harvest, thus these had to be placed again. Besides, after the rain the probes located mainly in the terrain depressions could not be used due to higher ground water level. This resulted in more difficult data processing, due to unequal step of individual time series.

Ground radon laboratory evaluation gave results with the accuracy artificially adjusted to the 10% of measured volume activity. This provides the bases for potential uncertainty analysis. Totally, 1841 samples arranged in 49 time series were extracted.

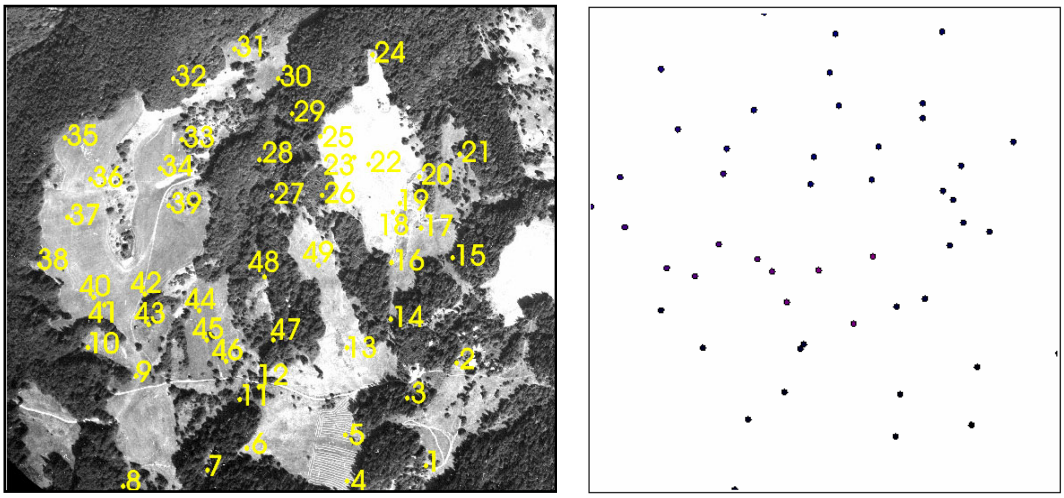

Fig. 2. Research area aerial photo and ground radon stable probes locations

Source data description

A large amount of data gathered does not allow their publishing, therefore just a sample of time series and chosen summary characteristics will be presented. In the Fig. 4 can be seen a sample of time series produced. High short-term temporal variability can be observed, while over longer periods a mean (red arrow) remains constant. Comparing individual charts shows certain similar features of radon volume activity temporal behaviour. These are mainly two radical increases between 5th and 13th day, and certain periodicity in global course. Without being analytically proved, it might be said that this account for the weather changes, mainly. This consideration comes from the continuous observation of ground radon volume activity in relation to other variables during the field data gathering.

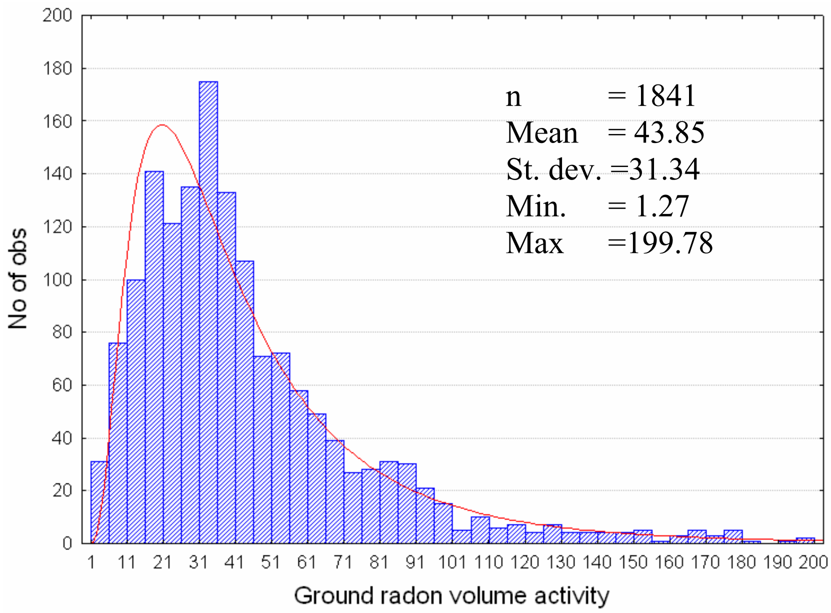

Fig. 3.The histogram of ground radon volume activity and related statistics. The lognormal distribution typical of ground radon volume activity can be seen.

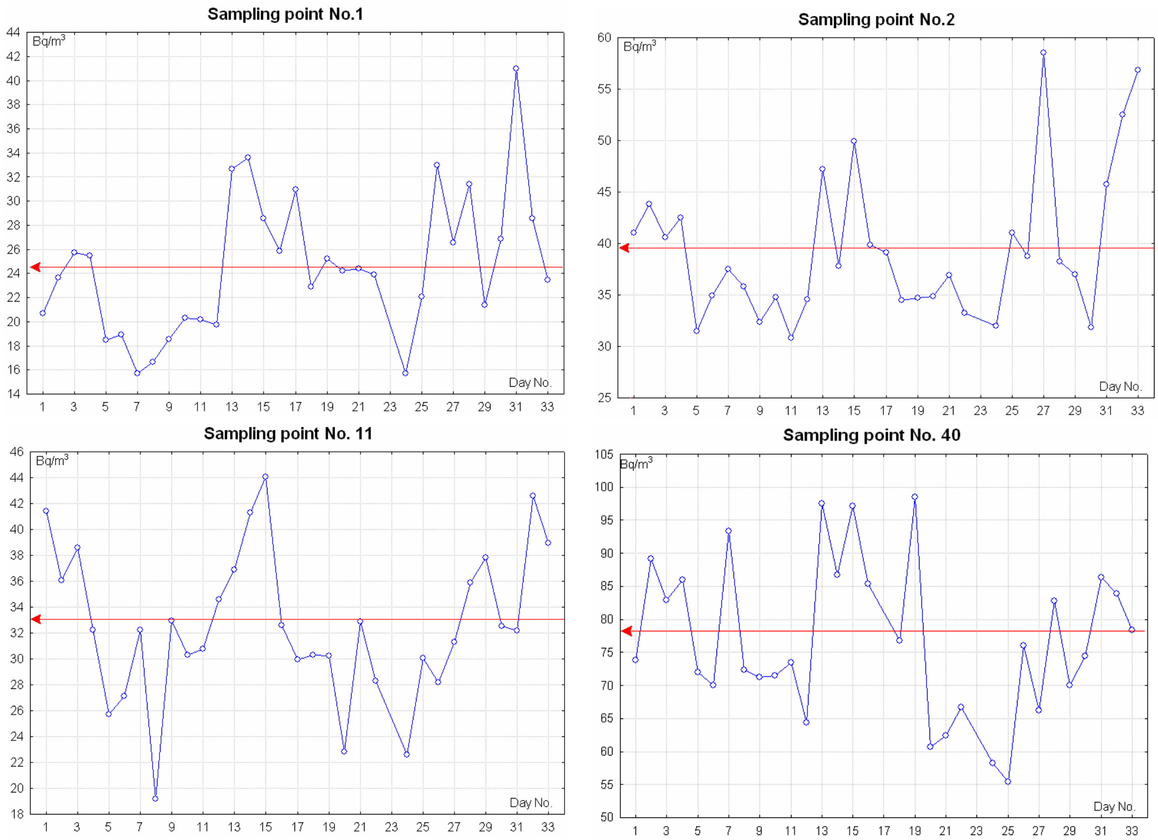

Fig. 4. A sample of ground radon samples arranged in four time series.

Derived characteristics

As derived characteristics, the second differences and acceleration coefficient, as described above were calculated. These will be used to analyse ground radon spatio-temporal dynamics and to design certain groups of sampling points exhibiting similar temporal behaviour. The chart showing acceleration index frequency distribution can be seen in the Fig. 5 This measure is outstandingly important for further analyses, since it characterize, although in generalized form, overall time series by one number, on the contrary to the sets of second differences.

The sample of four sampling points second differences can be seen in the Fig. 6. Their behaviour clearly indicates the periods exhibiting higher temporal variability and those stable. With regard to unequal step between individual measurements, second differences computation had to be adjusted. The solution (not just optimal) was to divide each first difference by time period between two consecutive measurements. This might work properly for small deviations (1-2 days)| from the supposed delay of three days, but the case of division by 8 or more days could be rather biased. To precise this procedure, sophisticated methods taking into account not only time series itself, but also other factors related to time series dynamics are required. This will be a focus of further research.

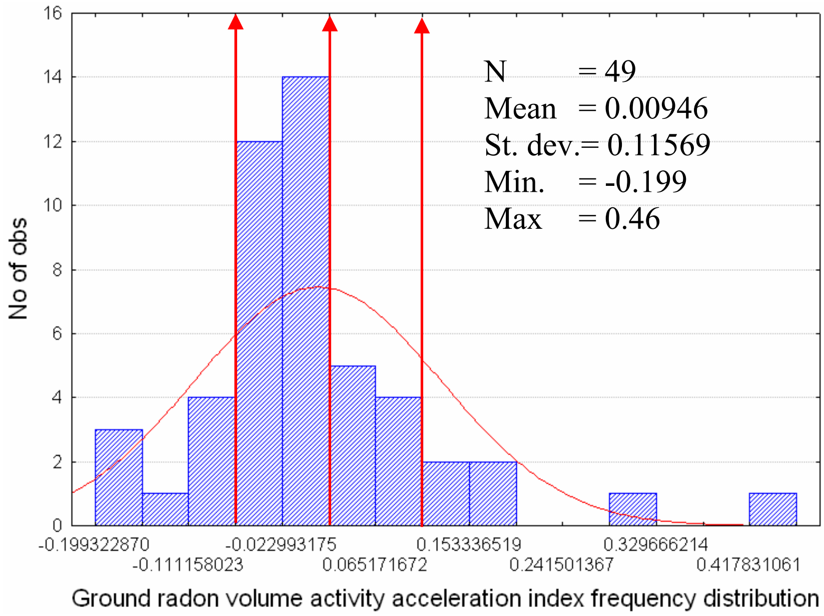

Fig. 5. The histogram of ground radon volume activity acceleration index and related statistics. Red arrows express remarkable changes of its shape, as thresholds of categories

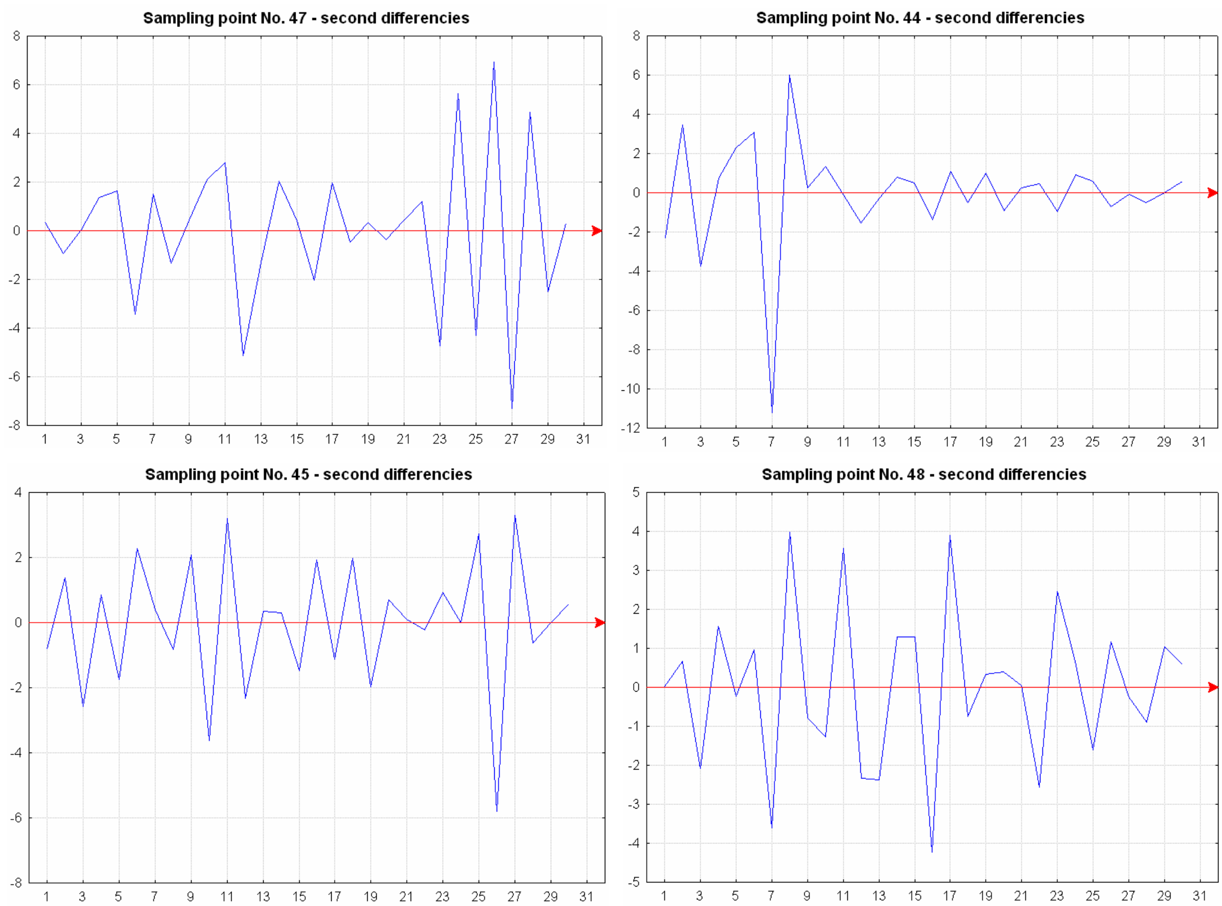

Fig. 6. A sample of second differences of ground radon volume activity. Different shapes of chart indicate various responses to weather conditions.

Ground radon spatio-temporal analyses

This part focuses on two areas of spatio-temporal analyses. The first one is to put respective temporal characteristics into the space, in a meaningful manner, and to analyse how these behave spatially. The second area is to classify the research area according to ground radon temporal behaviour and to interpret these categories. This is rather complicated task, because these should be delimited on the bases of time series as wholes, not by classifying summary characteristic such as acceleration indices. The main drawback of this procedure is that the acceleration index expresses time series dynamics by one number and the most important features of its behaviour, such as possible trend and periodicity are suppressed. The solution of that is the use of multivariate methods, namely the cluster analyses to determine the groups (clusters) of time series exhibiting similar behaviour. This is the focus of further research. Furthermore we focus on acceleration index spatial analyses and on certain features of its spatial structure.

Trend extractions

To leave aside the stochasticity of natural systems, the spatial trend as deterministic component is to be analysed. This provides, in highly generalized form, the main information on ground radon temporal variability spatial behaviour. In this study the third degree trend in the form

$$f(x,y) = A+Bx+Cy+ Dx^2+Exy+Fy^2 +Gx^3+Hx^2y+Ixy^2+Jy^3$$

was used (Ripley, 1981).

As can be seen, the central part exhibits quite equal temporal behaviour, while slight decrease can be observed in NW-SE direction. More radical decreases in NE-SW direction could not be taken serious due to insufficiency of the model. Polynomial functions used in the Trend Surface Analysis used to unrealistically undulate at the borders of the area under investigation, thus only the parts covered by data might be considered as true. Due to this undulation, also the statistics of this model quite differ from those of source data.

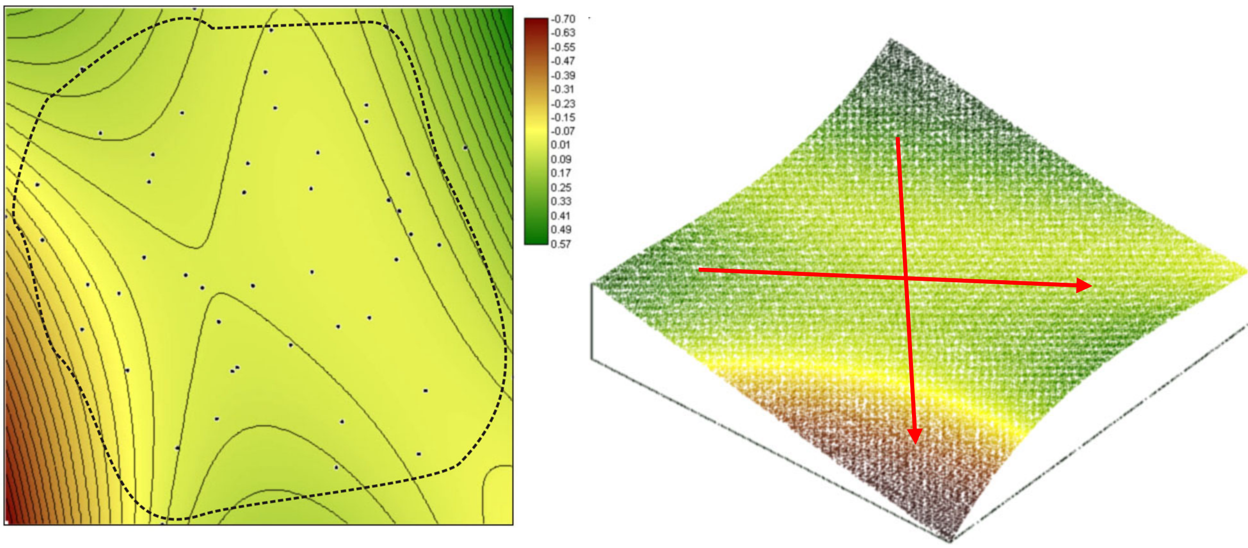

Fig. 7. Ground radon temporal dynamics spatial trend (schematic figure). The red arrow expresses the trend in the sense of significant decrease of acceleration index.

The interpretation of this behaviour is rather difficult. One answer might be the influence of microclimate, but since the proportional effect was observed (the variability increases proportional to ground radon volume activity magnitude), this kind of interpretations might be confused. For the time being the casual aspect of this behaviour remains unexplained.

Geostatistical approach

To constitute a model of ground radon spatio-temporal behaviour the ordinary kriging procedure was used. The problem we came across was certain number of outliers, i.e. pairs of points, which exhibits quite large differences in value when separated by relatively low distance. This strictly affects the variogram behaviour and almost pure nugget effect was observed. After removing 6 of the most critical points, the variogram cloud took on typical cone shape and the variogram stabilized at distance of approximately 300 meters (Fig. 8). The effort to construct directional variograms failed, despite slightly more continuous course of values following NW-SE direction, which can be seen in the trend model. Besides, further outliers occurred in particular direction, which could not be removed due to the relatively small number of source data. Therefore, the data were approached as isotropical, although this need not match the reality, exactly. In general, resultant isotropically designed model looks quite confusing, and no leading spatial structure can be inferred. On the other side, the variographic analysis proved spatially dependent character of individual sampling point acceleration indices, thus certain spatial laws controlling this phenomena exist.

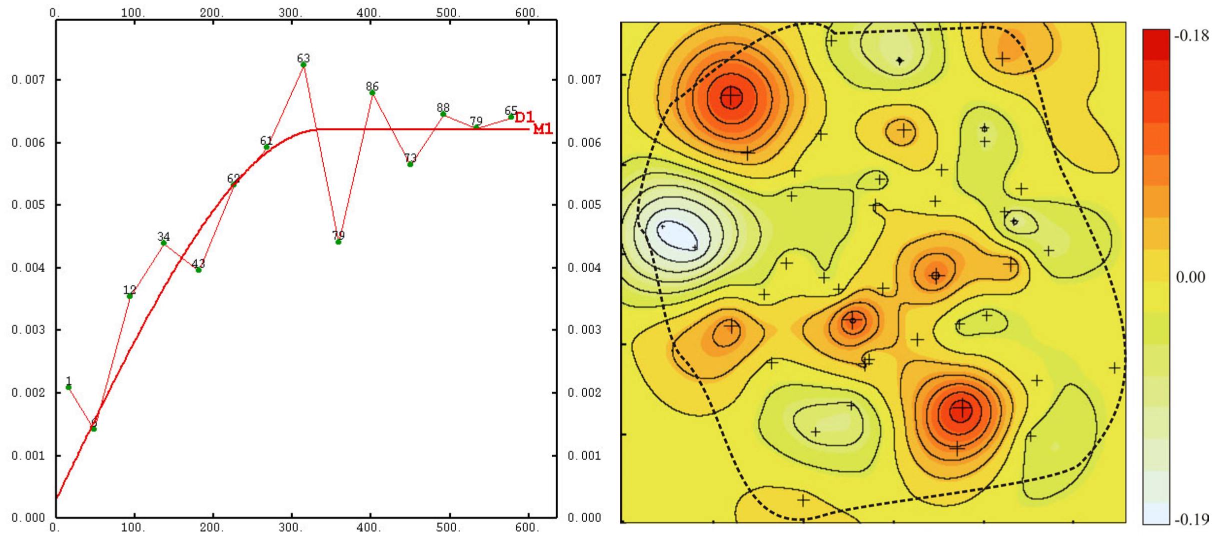

Fig. 8. The isotropic variogram (spherical variogram with nugget effect) and predicted model. The figures in variogram express the number of pairs used to compute respective variance value (schematic figures).

To classify this model into the categories with similar temporal behaviour, the idiographic classification according to Burrough (1986), following the multimodal histogram structure, was used. Since there are no conventions how to classify such a phenomenon, the homogeneity of individual categories appears as appropriate indicator of the threshold values. In this way, the four categories were delimited (Fig. 9). As can be seen, the first category 0.15-0.19 is due to the single extreme points and just the category ranging around the zero accounts for the most spacious part of the research area.

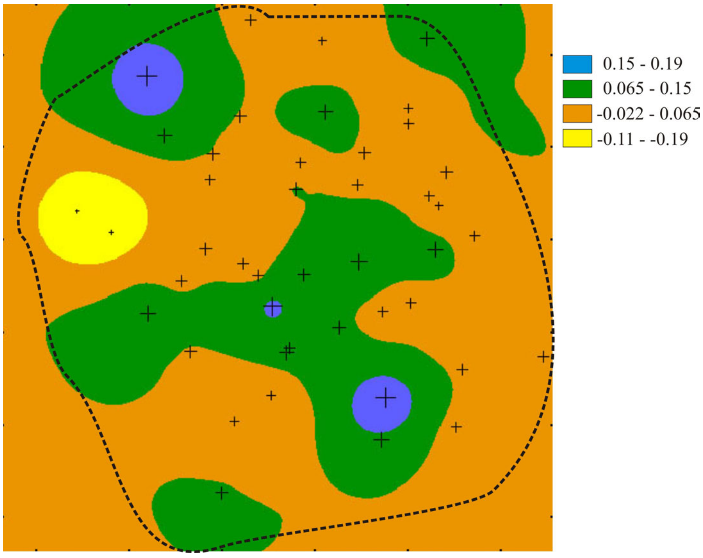

Fig. 9. Ground radon temporal variability model derived by means of ordinary kriging classified into four categories according to histogram in the Fig. 5.

Summary and discussion

In this study certain features of ground radon spatio-temporal behaviour were analysed. The sampling design appropriate for further analyses was proposed and all the fieldworks were successfully carried out. Totally, more than 1800 samples arranged in 49 time series were extracted. Individual time series behaviour were analysed and basic temporal characteristics were derived. Detailed analysis of all 49 time series goes beyond the scope of this paper, but, it might be said, without being analytically proved, these exhibits certain common features driven by several environmental condition, mainly those related to weather.

As the main quantity stepping into further analyses the acceleration index, as a summary characteristic of individual time series, was used. Furthermore, its spatial behaviour by means of the Trend Surface Analyses and chosen geostatistical tools was analysed. Very slight trend was noticed, the interpretation of which is difficult without confrontation with other environmental variables affecting ground radon temporal variability. These are, in a large extent, unknown.

The geostatistical analysis proved the presence of certain spatial laws forming this phenomenon, although no significant spatial structure was present After removing outliers, the isotropic spherical variogram reaching the range in 300 meters characterize acceleration index spatial variability. This was used to predict the continuous spatial model by means of ordinary kriging procedure the interpretation of which can bring better understanding of this phenomenon. To do so, the confrontation with other data is required, again. While individual time series behaviour is affected mainly by weather changes, in the spatial dimension mainly the factors related to relief morphometry and soil and geology features preliminary appear as the most important.

As can be seen, this paper has brought just the introductory information on ground radon spatio-temporal variability. In the future, it is necessary to classify individual time series as wholes, instead of their summary characteristics to determine the groups of sampling points exhibiting similar behaviour. The crucial point of this research is temporal characteristics dependence on chosen abiotical variables, what is the fact accompanying all this paper. Just the weather changes, terrain morphometry and geology and soil properties are those, which might explain some portion of ground radon spatio-temporal variability.

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References

BAKYTOVÁ, B., UGRON, M., KONTŠEKOVÁ, O., 1979: Základy štatistiky, ALFA Bratislava

BRABENEC, V., DIVILOVÁ, Z.,MACHÁČEK, O., 1982: Matematická statistika II, SPN Praha

BURROUGH, P.A., 1986: Principles of geographical information systems for land resources assesment, Clarendon Press – Oxford,

ĎUREC F., HLÁSNY T., PROKEŠOVÁ R., 2003: Geostatistical Approach to Radon Potential Mapping, IRPA Regional Congress on Radiation Protection in Central Europe, Bratislava, September, 24-26, 2003, on CD

HLÁSNY T., MATUŠKA J., ĎUREC F., KRÁTKA E., ŠKRABÁLEK P., 2003: Radón v podpovrchových vrstvách a jeho modelovanie v GIS, In: GIS Ostrava 2003, Rúžička, J.(ed.), on CD

HLÁSNY, T, ĎUREC F., 2004: Neurčitosť v priestorových analýzach, In: GIS Ostrava 2004, Rúžicka, J.(ed.), on CD

HÚLKA,J., BARNET, I., & BURIAN, I., 1994: The Relationship Between Indoor Radon and Data from Regional Radon Risk Maps in the Eastern Bohemian District, In Radon Investigation in the Czech Republic, V, Barnet, I. and Neznal, M. (eds.), pp. 45-54

ISAAKS, H.E. and SRIVASTAVA, R.M., 1989: Introduction to Applied Geostatistics, Oxford University Press

NIKODEMOVÁ, D. VIČANOVÁ M., HAVLÍK F., ĎURČÍK M., 1995: Radón a zdravie obyvateľstva, 1. vyd. Košice

OLIVER M. A. & KHARYAT A. L., 1999: Investigating the spatial variation of radon in soil geostatistically, GeoComputation 99, http://www.geovista.psu.edu

REIMER, G.M., 1995: Radon: Gas Transport in Soils and its Relation to Radon Availability: Hot Spot Identification and Flow Characteristics Near Structures, Project No. DE-AI05-87-ER60578, 21.p

ŠÁRO, Š., TOLGYESSY, J., 1985: Rádioaktivita prostredia, 1. vyd., Veda Bratislava

UNSCEAR, 1988: Sources, effects and risks of ionizing radiation. UNSCEAR. 1988 Report to the General Assembly, with annexes. United Nations, New York.

VLČEK,J.,1991: Fyzikální základy. In: Radonová problematika v bytech. Dúm techniky ČSVTS Ostrava, pp.5-11

MATHERON G., 1971: The theory of regionalized variables and its application, Les Cahiers du Centre de Morphologie Mathématique de Fontainebleau

RIPLEY, B.D., 1981: Spatial Statistics, Wiley and Sons, Inc., New York

ŠMELKO, Š., 1998: Štatistické metódy v lesníctve, Technická univerzita vo Zvolen

WACKERNAGEL, H., 1998: Multivariate Geostatistics, Springer - Verlag, Berlin