The indoor radon survey in Serbian schools: can it reflect also the general population exposure?

Zora S. Žunić, Peter Bossew, Nenad Veselinović, Francesco Bochicchio, Vincio Carelli, Janja Vaupotič, Olivera Čuknić, Rodoljub Simović, Zoran Vojinović, Dragica Kisić, Tore Tollefsen

Abstract. A systematic indoor radon survey in elementary schools of Serbia is underway since 2008. Its current first phase covers all elementary schools in predominantly rural communities of Southern Serbia. The design of the survey, its implementation and the current state of its realization is shortly described. Part of this paper is devoted to discussion of the question if this survey could produce results representative also of the radon concentration in dwellings and of radon exposure of the general population, discussing some statistical aspects of representativity which arose during the work, namely, if the implementation leads to an unbiased estimate of the targeted quantities.

Key words: indoor radon • survey • school • Serbia

Z. S. Žunić, N. Veselinović, O. Čuknić, R. Simović
Electro Chemical Etching Laboratory,
Vinča Institute of Nuclear Sciences,
P. O. Box 522, 11000 Belgrade, Serbia

P. Bossew✉
German Federal Office for Radiation Protection,
div. SW 1.1,
120/130 Köpenicker Allee, D-10318 Berlin, Germany,
Tel.: +49 0 30 18333 4231, E-mail: pbossew@bfs.de

F. Bochicchio
Department of Technology and Health,
Italian National Institute of Health,
299 Viale Regina Elena, 00161 Roma, Italy

V. Carelli
Safety and Environment Department,
Telecom-Italia S.p.A,
182 Via di Val Cannuta, 00166 Roma

J. Vaupotič
Jožef Stefan Institute,
P. O. Box 3000, 1001 Ljubljana, Slovenia

Z. Vojinović
Community Sokobanja,
23 Svetog Save Str., 18230 Sokobanja, Serbia

D. Kisić
Thermo Power Plant "Nikola Tesla",
44 Bogoljuba Uroševića Str., 11500 Belgrad, Serbia

T. Tollefsen
Radioactivity Environmental Monitoring (REM) Group,
Institute for Environment and Sustainability,
Joint Research Centre (JRC), European Commission,
2149 Via Fermi, TP 441, 21027 Ispra (VA), Italy

Received: 27 July 2009,
Accepted: 30 December 2009

Introduction

Exposure to natural radon and to its also radioactive decay products is considered a significant health risk. Even if the effect of exposure to low doses is still under discussion, there is no doubt that higher doses are detrimental. The main dangerous possible consequence is lung cancer, since the most important exposure pathway is inhalation and deposition of alpha particle emitters in the lung. The two relevant radon isotopes are ^{222}Rn, a member of the ^{238}U decay chain and ^{220}Rn, also called thoron (Tn), from the ^{232}Th chain.

While outdoor radon concentrations are in most cases around few Bq/m^3, within buildings high concentrations can be encountered, up to four orders of magnitude above the outdoor level. The main source is, in general, radon exhaled from the subsoil and accumulated in buildings through various transport mechanisms, depending on house construction and life habits. The source itself can be quantified as the geogenic radon potential (RP). Building materials (which contain natural radium that exhales radon), tap water and natural gas can also contribute to radon indoor, but high radon concentrations are generally due to radon arising from the subsoil only.

For these reasons, authorities in many countries in Europe and throughout the world have performed surveys in order to evaluate the distribution of indoor radon concentrations and identify areas where a relatively high proportion of high radon concentrations are encountered, with the goal to optimize radon risk reduction policies, which include taking up mitigation measures in existing buildings, and prevention measures in newly constructed ones. Although the first surveys started in the mid 1980s, in a number of European countries, no national representative survey has been made, so far. A review of national surveys in European countries can be found in [3, 22]. It has to be underlined that in many radon surveys, particularly those aimed to obtain a radon map, the issue of representativeness of the sample is not taken properly into account, thus potentially producing some biases in the results [10].

Despite the above limitation of existing data, since 2006 a European indoor radon map trying to harmonize existing data (with particular attention to measurements carried out at ground floors) is under production by the Joint Research Centre (JRC) of the European Commission [2].

Studies on radon in Serbia

No national representative data on the indoor radon exposure exist in Serbia, as well as in most of the countries of the Balkan region, so far. As preparation of the nation-wide survey, a number of regionally and thematically limited studies have been carried out since 1997. Several hundred residential houses in rural communities of South Serbia and Kosovo, Southeast and West Serbia, in Republic of Serbia (Bosnia and Herzegovina) and in Montenegro have been investigated since, and background information on local geology, building construction traditions and population lifestyle was collected.

During these field studies, indoor and outdoor Rn concentrations were explored, as well as radon and thoron in soil gas, radium concentrations in soil, radon and radium concentrations in well water [11] and external dose rate (air kerma rate), in order to get a picture of the overall natural geogenic radiation situation. Also temporal dynamics of radon was studied [23]. In recent years there have been tested different building materials on its radon exhalation properties aiming at triggering this issue to be taken into consideration on the state level [15, 16].

A particularly intensely investigated region is the town of Niska Banja (SE Serbia) and its surroundings. Known as tectonically active and renowned for its thermal waters and spas, very strong regional gradients of radon and thoron concentrations in soil and locally high indoor radon concentrations were found [24, 26, 27, 30, 31].

A subject which has been given increased attention for the last years, is thoron. Using measurement technique developed in Japan, some studies on indoor thoron concentration were made in Niska Banja and Gornja Stubla (Kosovo) [12, 24, 27, 28, 30], where, in addition to high radon concentrations (maxima above 6000 Bq/m^3), also rather high indoor thoron was found, up to 1500 Bq/m^3.

Moreover, some advanced and still to some degree experimental methods were applied, like retrospective techniques to evaluate retrospectively the average radon concentration on a period of many years on the basis of present measurements of ^{210}Po superficial and volume concentration in glass and sponge objects, respectively [12–14, 25, 29, 31].

The experience gained with these studies and the obtained findings formed the basis for developing a strategy to carry out representative surveys on indoor radon concentration in Serbia. As a first stage, a systematic survey on radon in all the elementary schools has been planned. Schools represent a particular but important indoor environment to be monitored as regards radon concentration. In fact, schools, and particularly the elementary schools, are spread in all municipalities and attending such schools is compulsory. Therefore elementary schools represent an indoor environment occupied by a high number of persons, both children and adults and a large fraction of lifetime is spent in schools by every person. For these reasons, surveys in schools were carried out in several European countries, and large surveys in schools are considered an important component of a national programme to evaluate indoor radon exposure, e.g. in Slovenia [21], Italy [6] and a province of Austria [8].

The current systematic survey in elementary schools of Serbia is shortly described within the next section. It is important to underline that this survey has been designed to be fully representative of radon concentration in elementary schools and of radon exposure of children and adults is these schools. Actually, the survey will cover all these schools, so that there are no problems of possible sampling bias and of estimate precision.

The main purpose of this paper is to investigate if (and to what extent) this survey (and the results that will be obtained) could be considered representative of radon concentration in the main indoor environment, i.e. dwellings.

Incidentally, while the measurement results of the survey in schools of Serbia will provide a national decision base in radon matters in the first place, it is also planned to evaluate how the measurement data could be used as input to the aforementioned European indoor radon map. For mapping purposes, indoor radon is often restricted to ground floor, in order largely to get rid of the "longitudinal" variability of indoor Rn, seen as variable over $\Re^2$ (i.e. as projection onto the ground level of a building), which is due to systematic differences of radon owing to factors such as floor level, air exchange rates, etc. Of these, floor level contributes most to longitudinal variability. For further discussion of longitudinal variability, see [5] and [1].

Short description of the Serbian national survey on radon concentration in elementary schools

Measurement method

The detectors are CR-39 pieces (2.5 × 2.5 cm, 1 mm thick) housed in small plastic cases (Fig. 1), model TASTRAK made by Track Analysis Systems Ltd., Bristol, UK, and supplied by the Italian National Institute of Health (INIH), Roma.

The films are evaluated (etching and counting of track density) at the Radon Laboratory of the Italian Telecom Company in collaboration with the INIH. The method is chemical etching for 1 h in a thermal bath (with stirring) containing a NaOH solution 6.25 M at a temperature of 98°C.

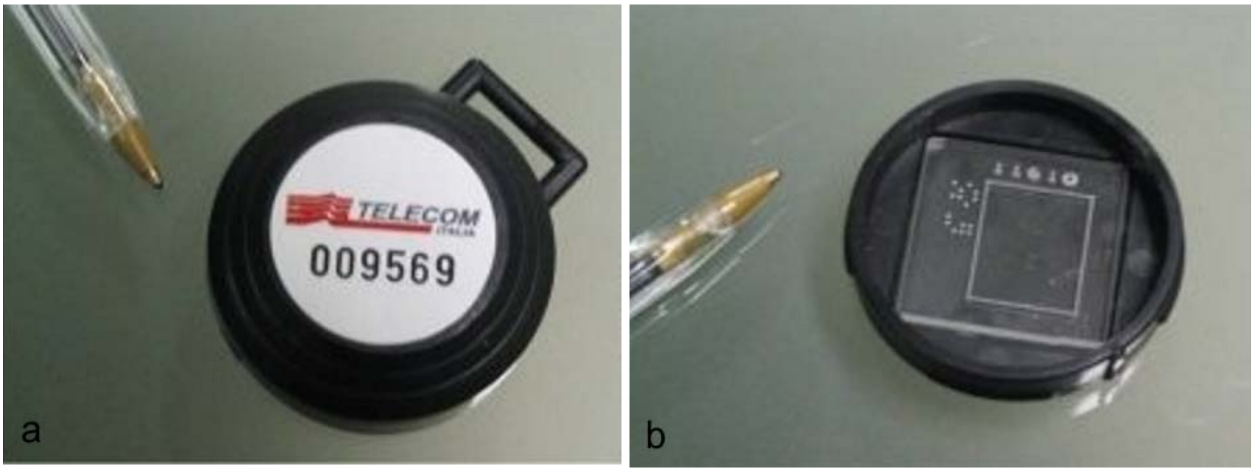

Fig. 1. Base (a) and cap (b) of a TASTRAK Rn detector. On the right picture the film can be seen.

The thoron question

In principle, CR-39 detectors do not discriminate between radon and thoron. The design of the measurement device is, however, such that the very small opening (the gap between case and cover) acts as a very effective diffusion barrier for thoron. Based on experiments with very similar devices, one can assume that the relative efficiency for thoron is up to 2–3% of that for Rn. The actual sensitivity of the radon device used in this survey has been planned to be experimentally evaluated in the near future.

Position of detectors

In every ground-floor classroom two detectors have been deployed simultaneously, closely connected by a string or a wire. The purpose is quality assurance of measurements and thus the results; it happened already (although very rarely) that one detector was lost. The variability between the results of the two detectors will also give information about the uncertainty of the results, to some degree.

In addition, detectors have been located in the teacher's or the director's room (if this exists), and also in some higher floor classrooms; but these are very rare in rural elementary schools.

The detectors are located mostly on shelves or cupboards in places which appear not to be used for storing objects or for other activities. Frequently, the detectors are fixed directly on the wall on hooks, nails, frames of the pictures etc.

A potential problem is the location close to walls. Very close to walls, thoron concentrations can be considerable, even if they are insignificant in the main volume of the room [9]. Although the detectors seem to be quite insensitive against thoron, one must ask if high thoron concentrations near walls may still introduce an estimation bias.

Protocol

Each site is represented by a file consisting of protocol (one for each visit) and data sheet. The protocol includes the following data:

- site: district, municipality, village, name of school;
- GPS coordinates (map if available);
- type of room, floor level, location of detector in the room;
- date of detector deployment or collection;
- detector codes;
- observations, remarks.

The data sheet contains information on school and municipality:

- school: construction year, construction type (building material), photo;
- school: number of pupils and teachers;
- municipality: area and population of municipality, number of schools;
- administrative data and documents.

Implementation and experiences

So far the Serbian survey on indoor radon concentration in elementary schools has involved only rural areas (including capitals of the communities, in general small towns). It is carried out municipality by municipality, in that during one "campaign" – usually a few days to one week – detectors are deployed and/or collected in the schools of one municipality. First, the Vinča Institute (VINCA) in Belgrade contacts municipality authorities, explaining the project to them and offering to perform the radon survey in exchange for logistical support. A contract is made between the VINCA and the municipality, the schools are identified and the actual campaign is planned. Schools are visited and detectors deployed. After about half a year, the detectors are collected and new ones deployed, and again collected after another half year, in order to obtain a full year of exposure and, therefore, to take into account seasonal variations of radon concentration.

Only elementary schools (attended by children up to 10 years, corresponding first to forth grade in the Serbian system) are chosen systematically for the survey. Firstly, secondary schools are much less spread over the territory than elementary schools and thus we think that including secondary schools would compromise the first of the assumptions in section on representativeness, below; secondly – more pragmatically – the chance of loosing detectors appears higher in secondary schools, due

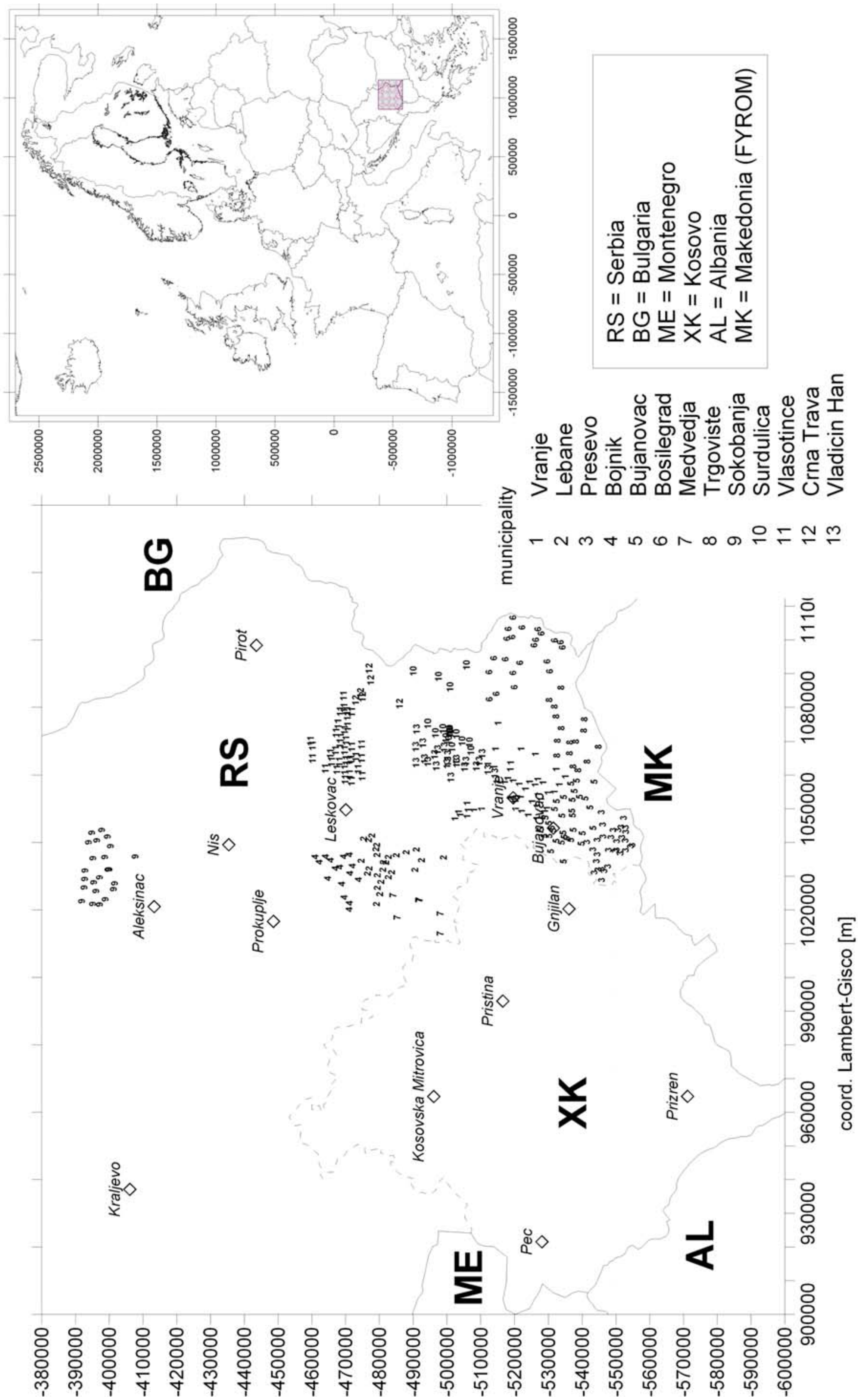

Fig. 2. Sampling points in Southern Serbia, by end June 2009. The positions of the figures in the map represent the sampling locations; the values are related to the municipality codes in the legend.

to the usually less disciplined behaviour of the students. However, also in a few secondary schools detectors were deployed for providing additional information.

The cooperation with communities has been very good, and also school directors and teachers have generally been motivated to cooperate. Thus, the recovery rate has been about 99% in the first communities, for the first 6-month deployment, which can be considered an excellent score. The scheme is logistically relatively simple and cost-effective.

At the end of June 2009, in 13 communities (out of 30 non-city communities in Serbia) the first half-year batch of detectors has been deployed. In six of these, the first batch has been collected during spring 2009 and the second one deployed.

In total, at 340 schools 1836 detectors have been deployed from September 2008 until June 2009 (Fig. 2), regarding the first (13 communities) and second field visit (after 6 months in 6 communities). No measurement results are available so far.

Current state

In Fig. 2 the sampling sites, which have been visited at least once, are displayed in a map of Serbia, marked by the community corresponding numbers. The variable density reflects the variable population density in the mostly mountainous areas of South Serbia.

Aggregated to the scheme of the European indoor Rn map (10 × 10 km cells aligned to a defined coordinate grid [4]), the sampling density equals 4±2 per cell (Median ± MAD, MAD – median absolute deviation, $\mathrm{MAD}(x) = \mathrm{MED}\,(|x - \mathrm{MED}(x)|)$, a non-parametric dispersion measure). For comparison, over Europe the value equals 5±4, but it is very different between countries. Its range is between 1 and 23 993 measurements per cell [4]. The medians (± MAD) are between 2±1 and 61±50 measurements per cell.

Can the survey in Serbian elementary schools reflect also the general population exposure to radon in dwellings?

In the following we will discuss if and how radon measurements carried out for the survey in Serbian elementary schools can be used to try to estimate the exposure of the general population in dwellings. In particular, the question is if the average of all measurements in schools in a spatial unit (municipality or ultimately the whole country) can be considered an unbiased estimate of the population-weighted indoor Rn concentration in buildings in which people spend the largest fraction of time, i.e. their home.

Taking into account that, in the present survey, one-year radon concentration measurements have been carried out in classrooms largely at ground floor, these radon measurements could be representative of radon concentration in ground floor dwellings under the following assumptions:

– the spatial density of classrooms equals the population density;
– schools are considered equal to homes in general, in terms of their properties with respect to involved radon;
– temporal usage patterns of schools are equal to the ones of homes.

These assumptions will be discussed in more detail below.

If the above assumptions hold, then, on the average, the Serbian survey – in its current stage of design, restricted to rural areas – will result in an unbiased estimate of the exposure of the general population to indoor Rn at ground floor of dwellings, which is a conservative (i.e. an upper limit) of the exposure of general population in dwellings, part of which is located at floor levels higher than the ground floor.

If the assumptions happen to turn out largely violated, the survey in elementary schools cannot be used also (besides its primary objective) to obtain an unbiased estimate of radon exposure in dwellings, and a specific national survey has to be designed.

Statistical considerations

We think that it is necessary to discuss the above assumptions in more detail. Ultimately one has to test the hypothesis that the chosen design allows estimating the target quantity, exposure (or a proxy of it). The first subsection is devoted to general concepts, namely the notion of "representativity" and the spatial pattern of sample locations for surveys, while the subsequent sub-sections discuss actual issues of the Serbian survey.

General

We would call results deduced from a sampled quantity representative for a target quantity, in a given spatial unit, if the expectations of the two are equal in that unit. This condition is called unbiasedness. For example, the sampled quantity can be "annual mean indoor radon concentration in ground floors of elementary schools", the target quantity, "annual mean indoor radon concentration in ground floors of dwellings", and the spatial unit, municipality.

A bit more general, also a transformation of the sampled quantity may still allow unbiasedness. For example, if one finds out that multiplying the Rn(school) value (mean over a unit) with a constant factor gives the Rn(dwelling) value (mean over the same unit), the condition would still be fulfilled.

Furthermore, one would wish that not only the expectations are equal, but also that estimates of the expectations (the sample arithmetic means within the spatial unit) are reasonably well correlated, e.g. in terms of correlation coefficient. This is equivalent to asking the variance of the difference of the sampled and target quantities to be as small as possible. For example, one would like that a scatter plot of measured Rn(school) vs. Rn(homes) looks like a cloud of points concentrated around a straight line (the linear regression line) with intercept zero and not too much scattering around the line. Each point in the scatter plot would represent the means of schools and homes within a given spatial unit, like a village or a municipality.

As indicated in the example, these conditions can be tested by regression, if a sufficient number of samples is available.

The next question is how to estimate the expectation of a quantity within a spatial unit. Formally, the arithmetic mean of the samples within the unit converges towards the expectation with increasing sample number (central limit theorem) – if the sampling scheme or pattern (i.e. the distribution of sample points in the unit) is such that the whole area of the unit is reasonably uniformly covered.

Two different sampling designs are shown in Fig. 3. Obviously, the measurements (samples) resulting from the uniform scheme of samples, left graph, allow an unbiased estimate by arithmetic mean of the expectation within unit *U*, which the right scheme will not achieve. However, a second thought is necessary here. Imagine that one wants to estimate the mean population density weighted radon concentration within unit *U*, as proxy of exposure, and not the spatial mean within *U*; the latter is the mean over real or hypothetical buildings uniformly distributed within *U*. If one is ultimately interested in exposure and risk, one will try to estimate the first quantity, while the second one is of interest if one wants to assess the geogenic radon potential.

If the mean exposure or population weighted radon concentration within *U* shall be estimated, one has two reasonable choices of sampling scheme: (1) one chooses a uniform (regular or random) pattern (Fig. 3, left) and computes the weighted arithmetic mean as estimate of the target quantity, where the weighting factors are the local population densities; (2) the sampling pattern is chosen denser where more people live and sparser in less inhabited areas, i.e. the sampling density set proportional to the population density. Mathematically, the result is the same (asymptotically with number of samples), but option (2), or a sampling pattern like in Fig. 3 (right) is more efficient.

Returning to the question of estimating the expectation, a more sophisticated way is to account for the spatial auto-correlation structure of the target variable; this is what kriging or conditional simulation do. Also the choice of sampling pattern is then less critical; the drawback is the bigger computational effort. A different, also model-based approach is log-normal estimation, where one estimates the parameters of a log-normal distribution out of the data within *U*, possibly refined by Bayesian reasoning, and derives the estimates of mean and variance from the distribution. This method has proven particularly efficient if one is interested in exceedance probability, that is, the probability that within *U* the radon concentration is above a threshold. Once measurement data are available we shall certainly devote greater effort to the estimation problem.

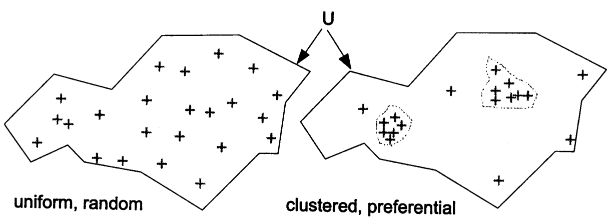

Fig. 3. Two sampling designs.

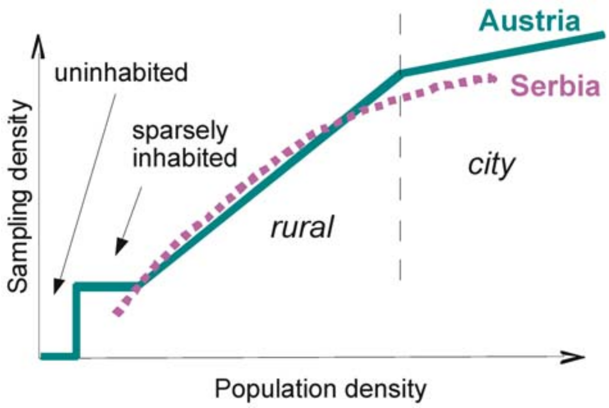

Fig. 4. Intended sampling density in Serbia, and as initially planned in Austria, for comparison.

Demographical representativity

The questions here is whether the number of schools, or classrooms, per municipality is basically proportional to the number of inhabitants per municipality? The planned design is such that the number of detectors deployed to ground-floor classrooms is proportional to the population in the "attraction basin" of a school, which means a sampling scheme with sampling density equal to the population density (Fig. 4). The first data indicate (although not statistically significant) that the assumption is roughly fulfilled in rural areas of Southern Serbia (Fig. 5, top). In both figures, the Austrian

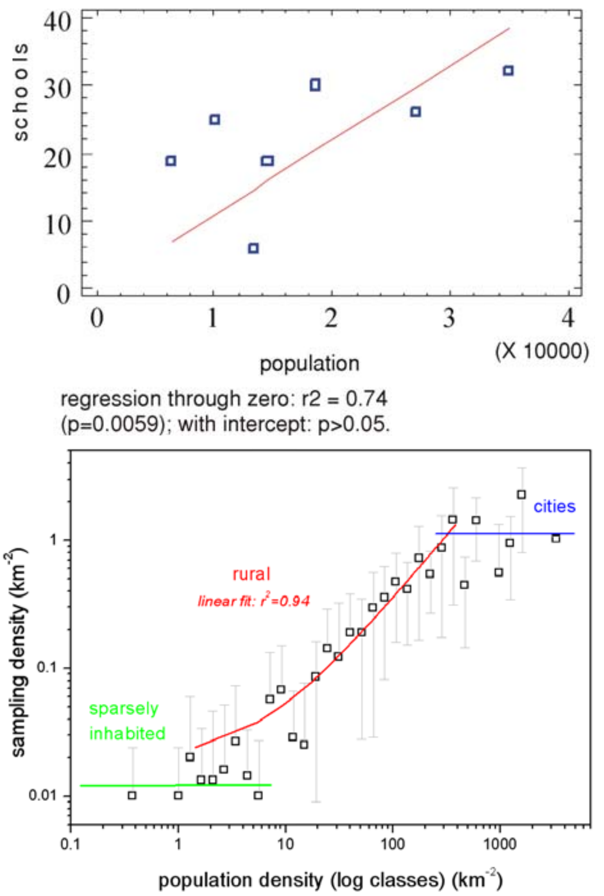

Fig. 5. Actual spatial sampling designs: top – as realized so far in Serbia, based on preliminary demographic data; down – Austria, finished survey. Compare with the plans, Fig. 4.

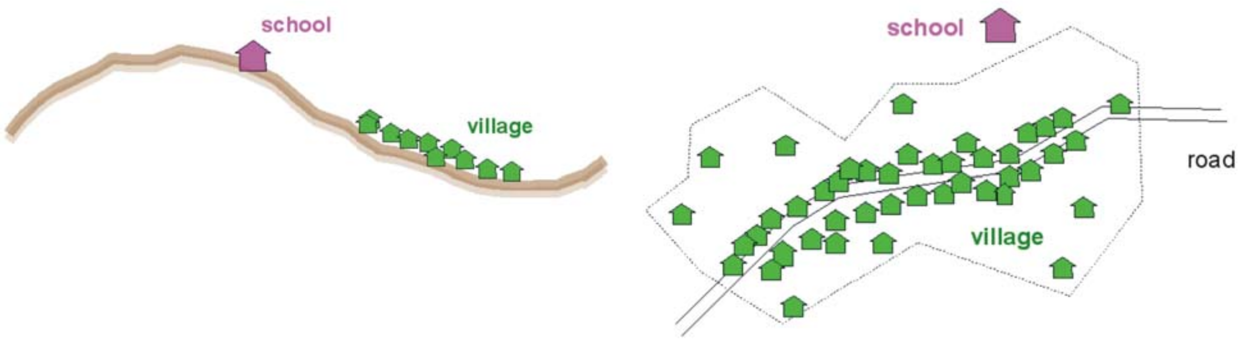

Fig. 6. Geographically unrepresentative locations of schools in relation to villages.

planned design, and as finally achieved, are shown for comparison.

Further demographic data are needed to decide on this. In case it is fulfilled only region by region, one will have to develop a kind of bias correction to compensate for a systematic error which may result from the violation of the assumption.

Spatial representativity

Next, one must ask if the locations of schools within villages are representative for residential houses, as far as the geogenic RP is concerned. Put statistically, is the RP(school) an unbiased estimate of the expectation of the RP on the site of homes of that village? By superficial visual inspection, this does not seem to be the case very often. It seems that often schools were built in prominent, untypical locations, like on hills or upslope above the village, or a bit outside, as shown schematically in Fig. 6.

It should still be investigated more systematically if this may introduce an estimation bias.

Building styles

One assumption of the design is that, on the average, radon concentration in a school is the same as in a hypothetical residential building at the same place, given the same usage pattern (see below), or as weaker assumption that the mean radon concentration in schools over an area (like a village or a municipality) is the same as the mean radon concentration in homes, in the same area. This requires that the influence of construction style on the radon concentration is the same for both building types. From visual impression, this is not obvious: homes and schools appear to be constructed differently. It must therefore be investigated whether these differences make a difference with respect to radon. We want to mention the results of three surveys of radon in schools, i.e., in Slovenia, Italy and Austria relative to radon in homes. The examples show that inference from schools to homes, as radon is concerned, must be done with caution, and that more discussion of the representativity issue is needed.

Slovenia

Within the Slovenian indoor radon programme, three radon surveys were carried out in the period from 1990 to 1994. Radon has been measured in indoor air of about a thousand randomly selected residential buildings [7], and in practically all the kindergartens [20], and schools [21]. Elevated radon levels in the residential buildings appeared to be failures in construction of the basic slab, as well as cracks and other damages occurred in it due to aging. The same reason for elevated radon levels has been also observed in some of the kindergartens and schools, but in the majority, a sub-floor channel running all along the building (conveying, e.g., tap water and central heating tubes) has been identified as the major radon source.

In kindergartens and schools radon concentrations differed substantially, showing for schools the geometric mean 1.4 times higher than in kindergartens. Different type of design and construction is the most probable reason for this. A great part of kindergartens was built in the 1970s and 1980s, following newer construction design and technology, different from that used for the majority of older schools.

At 53 places, all located on the river sediments, radon was measured both in indoor air of the school and in soil gas nearby. No correlation between the two was observed, pointing out that type of construction had a predominant influence on the indoor radon levels [17, 19].

In a village in a radon-prone area, radon was simultaneously monitored in a school and in 24 homes. Radon concentrations in the school exceeded those in homes for a factor of about 2 [18]. According to the above findings, radon levels should not be simply interpolated from school to residential buildings, and a great precaution is needed to do so.

Italy

The results of radon surveys in schools and kindergartens of six Italian regions was compared with the radon concentration measurements in dwellings of the same regions, carried out in the framework of the Italian national representative survey of natural radioactivity in dwellings [6]. Despite some significant differences between schools and dwellings have been observed in the regional average radon concentration, these differences tend to reduce when comparison is restricted to the same municipalities and the same floor levels (ground floor). However, due to the limited number of sampled dwellings and schools, the uncertainties of the estimates in the restricted analysis are quite high and did not allow revealing small differences [6].

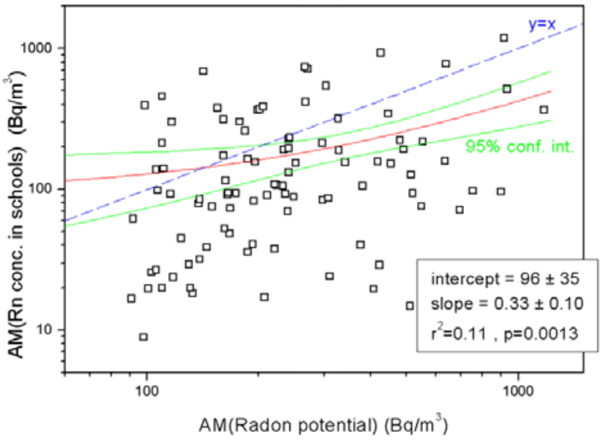

Fig. 7. Scatter plot and regression of radon concentrations in schools vs. radon potential (Friedmann-RP). Means taken over municipalities. For details see text.

Austria

In the late 1990s a study on radon levels (among other possibly hazardous air pollutants) in schools was conducted in a province of Austria [8] because it was suspected that schools might be systematically different from homes, in respect to indoor radon. The data can be compared to the results of the Austrian indoor radon survey in residential areas in the same region. The graph, Fig. 7, shows the arithmetic mean of radon concentrations in ground floors of schools per municipality, vs. the mean RP per municipality. The RP [5] is roughly equal to the indoor concentration in ground floor (modulo some more normalizing factors, which contribute much less than floor level).

If the assumptions were correct that schools represent homes, the intercept of the linear regression (note that due to the log-log scale the straight line appears curved) should be 0 and the slope equal to 1 (both up to statistically insignificant deviations). This is evidently not the case, so that the representativity of schools is doubtful in this case, even if a significant ($p = 0.0013 << 0.05$) correlation exists, which, on the other hand explains only $r^2 = 11\%$ of the variability of the arithmetic mean per municipality in schools. The reason has not yet been clarified.

Temporal representativity

Residential houses are generally inhabited all year round, while schools are closed during weekends, during summer (normally July–August) and for a short period (up to 15 days in Serbia) during winter vacation (December–January). Also apart from this, most striking difference, the "temporal usage pattern" is quite different in schools and homes. One may, therefore, ask whether the long-term mean radon concentrations in schools are systematically different from the ones in homes, even when not considering other sources of possible bias.

As it is well known, indoor radon levels greatly depend on living habits in homes and working regime in public buildings. Additionally, in public buildings, such as schools, ventilation mode plays an important role, either based on air-conditioning (not frequently used in this part of the world) or not [19]. Continuous radon monitoring in public buildings has shown that radon concentration remains at a constant maximum during weekends, in addition to maxima during every night, thus contrasting with the situation in dwellings, where rooms may be even more ventilated (by opening windows) during this time because people stay at home, and, hence, radon levels are low. This is not in favour to the equivalence of radon levels between school and residential buildings. On the other hand, one should bear in mind that the difference between one school and another, due to specific ventilation and working regime, may be bigger than between a school and a dwelling. In any case, again we think that a great precaution is needed in inferring to radon levels in residential buildings from the ones measured in schools.

In the regional Austrian radon survey in schools, the mean radon concentration during school working hours only was measured in addition to the continuous mean in a number of schools. The ratio work hours/continuous was found 1.27, not regarded significantly different from that given the large range between 0.59 and 2.72. In any case, the result shows that continuous measurements may lead to misestimate of the actual exposure; but the same problem applies to measurements in homes. (It should be also kept in mind that exposure also depends, apart from the Rn concentration, on the equilibrium factor between radon and progenies and the attached fraction; these parameters which are not being measured in general can vary widely and are difficult to predict).

Conclusions and outlook

The Serbian national radon survey in elementary schools is well under way since 2008, and its implementation goes without obstacles so far. By end-June 2009, 13 communities have been visited at least once and six twice (three visits are necessary at each site).

The current phase, survey of rural areas, will still take further 2–3 years, given the limited resources. For urban regions a particular sampling design has to be chosen, which can be expected to be more demanding logistically.

Also a number of statistical questions remain to be answered, which relate to problems of representativity of the results in schools as regards radon exposure in dwellings. This will probably require additional, specifically designed local surveys and maybe a specific national survey on radon in dwellings.

If sufficient measurement results become available, we will start to explore which mapping method is the most appropriate. The main methods are (a) univariate modelling within spatial units (such as grid cells or administrative units), where statistics like the arithmetic mean, or excess probabilities are assigned to the units; or (b) geostatistical methods which account for spatial autocorrelation. Method (a) may be refined by Bayesian reasoning, while (b) may include external deterministic predictors.

Acknowledgment. We are grateful to F. J. Maringer (Boku, Vienna), H. Friedmann (University of Vienna), and Upper Austrian Provincial Government (Upper Austrian School Survey). We wish to thank G. Ferrigno and C. Cordedda (Telecom-Italy) for radon detector etching and counting, and C. Carpentieri (Italian National Institute of Health) for radon detector preparation and measurement data handling. The help and engagement of all teachers and the pupils of the Serbian schools is highly appreciated, and particularly of those colleagues from communities whose support is indispensable for this project. The Serbian radon survey is funded by the Ministry of Science of the Republic of Serbia and the University of Belgrade, Project 141019B.

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