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# Mapping the Geogenic Radon Potential and Estimation of Radon Prone Areas in Germany

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The geogenic Rn potential (RP) is conceptualized to quantify what "Earth delivers" in terms of Rn. The RP indicates the potential risk at a location or as mean over an area, which can arise due to indoor Rn in a building, originating from geogenic Rn, and depending on its physical characteristic regarding Rn infiltration. In geogenic Rn prone areas (RPA) which are ones with RP elevated after given criteria, the probability of encountering elevated indoor Rn concentrations is also elevated, again depending on house characteristics.
In Germany, the RP is estimated from Rn concentration in soil air and soil permeability, with geology as auxiliary categorical predictor. The hazard level is "calibrated" by relating the RP to indoor Rn concentrations in standardized types of dwellings, which by applying "hazard thresholds" leads to delineations of RPAs. The purposes of identifying RPAs are more efficient allocation of resources to intensified surveying, remediation and possibly implementation of building codes. It is also part of the national "Rn action plan" required by the new EU Basic Safety Standards.

We present an outline of methodology and show how RP and RPA maps can be generated. As examples, RP and RPA maps of Germany are shown.

*Key words:* Radon potential, radon prone area, mapping, Germany

## 1. Introduction

It is widely acknowledged that radon (Rn) is a hazardous pollutant. As epidemiological studies have shown (for a summary see WHO Radon Handbook[1)]), also relatively low concentrations lead to a detectable rise of the lung cancer rate. Indeed it may well be that there is no lower threshold of the detrimental effect of Rn. It is also known that in general indoor Rn contributes the dominant part to the dose budget of the population; even more with the new dose conversion factors (Harrison and Marsh[2)]) which are about three times as high as the currently used ones from ICRP 65[3)].

These insights led to increasing awareness also of regulators. In 2014, this resulted in the new Basic Safety Standards (EU-BSS) for protection against ionizing radiation of the European Union[4)], which also cover exposure to indoor Rn at home and at work places. The BSS is European law, which has to be translated into national legislation by Member States. A *maximum* reference value (RV) of 300 Bq/m³ has been set (article 74, par. 1; article 54, par.1 for workplaces), in line with ICRP 115 (part 2)[5)]. RV means that the long-term mean concentration should not be higher than the value if technically reasonably achievable[1]; otherwise,

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mechanisms of general radioprotection apply. (It should be said that with the new dose conversion factors, 300 $Bq/m^3$ correspond to approximately 18 mSv/a, using common occupancy and equilibrium factors). The EU-BSS also requires the Member States to develop a radon action plan aimed to improve Rn prevention and mitigation (article 103, annex XVIII). Among other issues, the Rn action plans include delineation of radon prone areas (RPAs), although the term does not appear explicitly in the text (article 103, par. 3). The purpose of RPAs is information about where possible Rn problems preferentially occur and as guideline for more efficient allocation of resources in terms of regional legislation (e.g. implementation of building codes), possibly subsidies for remediation measures, additional surveys, etc.

In this paper, the German radon potential (RP) map is presented, focussing on methodology. The second topic is the method how to derive a RP threshold for defining radon prone areas, based on thresholds for indoor Rn.

## 2. Definitions, concepts and data

### *2.1. The geogenic radon potential*

The geogenic radon potential (RP) is conceptualized as to quantify "what earth delivers" in terms of radon, or as put on the web site of the responsible authority of Saxony (Germany), "The radon potential is the property of soil to release Rn into soil air, and together with it make it available at ground surface."[2]. Indoor Rn concentration is the product of the RP and anthropogenic factors. This means that high RP does not necessarily imply high indoor Rn, neither the reverse, because also low RP can lead to high indoor Rn if infiltration is high. Instead, the RP measures the hazard, or potential risk, which becomes actual risk under certain additional conditions, as given by "radon prone" building styles and living habits.
A number of quantities have been proposed for measuring the RP. Here we use a definition essentially following[6)],

$$RP := C_\infty / (-\log_{10}(k) - 10) ,$$

with $C_\infty$ = the equilibrium Rn concentration in soil air ($kBq/m^3$) and k the air permeability of the ground ($m^2$). (The original definition has been slightly modified for physical plausibility.) Other definitions are based on Ra concentration and emanation power[19)], standardized indoor concentration[20)] or the probability that indoor Rn concentration exceeds a threshold[21-24)]. RP classes were defined by different authors by cross-tabulation or combining of controlling factors like geology, topographic features and classed soil Rn and permeability[6, 25-28)].

### *2.2. Geogenic radon prone areas*

Essentially two types of concepts of a radon prone area (RPA) exist. The first is based on actual indoor Rn concentrations and the second one on the geogenic RP. For the *first notion*, a geographical unit is defined RPA, if a statistic related to indoor Rn exceeds a threshold; this may be simply the mean over dwellings in that unit or a spatial mean, or a minimum probability that a dwelling or a point of an interpolated surface exceeds a threshold or a reference value (RV) understood as a threshold. A property of this notion of RPA is that the status of an area can change with building styles and living habits changing over time, connected to changing infiltration rates into buildings and air exchange rates, i.e. the anthropogenic controlling factors.

The EU-BSS[4)] (article 103, par. 3) suggests as conceptual definition, "areas where the radon concentration (as an annual average) in a significant number of buildings is expected to exceed the relevant national reference level". In a previous draft of the BSS, a more specific definition had been proposed: "Radon-prone area means a geographic area or administrative region defined on the basis of surveys indicating that the percentage of dwellings expected to exceed the national reference level is significantly higher than in other parts of the country" (EC 2011[7)], article 4, definition 71, p.28). Put more formally, a unit U is RPA if the probability that the long-term annual Rn concentration C(x) exceeds a RV is a given times higher as the probability in the country B (or a given region) as a whole:

$$U \subset B \text{ is RPA if}$$
$$\text{prob}[C(x) > RV;\, x \in U] > \alpha\ \text{prob}[C(x) > RV;\, x \in B] \qquad (1)$$

The definition has not been elaborated in detail in the final version of the BSS. One of its characteristics is however, that the definition varies between countries and would cause inconsistency across borders: for example, an area, which is RPA in the Netherlands, where Rn concentrations are very low altogether, is no RPA across the border in Germany, although geologically the same, because mean indoor Rn concentration is higher in Germany for geological reasons. On the other hand, this definition can be expected to reduce to an extent the temporal variability of the status of an area as RPA, since in general the anthropogenic controlling factors will change in a similar manner locally and regionally, so that this change approximately "cancels out" from the RPA definition.

The *second concept* rests on the geogenic factor, which

[1] Article 4, definition 84 of the EU-BSS[4)]: "reference level" means in an emergency exposure situation or in an existing exposure situation, the level of effective dose or equivalent dose or activity concentration above which it is judged inappropriate to allow exposures to occur as a result of that exposure situation, even though it is not a limit that may not be exceeded.
[2] Original in German: „Das Radonpotenzial bezeichnet die Eigenschaft eines Bodens, Radon in die Bodenluft freizusetzen und mit dieser an der Erdoberfläche abzugeben.";
http://www.umwelt.sachsen.de/umwelt/strahlenschutz/28756.htm , accessed 28.4.2015

is, in general, the most important contributor to indoor Rn among the geographically variable factors. Other factors of this type are regional trends in building styles and living habits, depending on climate and cultural habits. This factor is quantified by the RP. According to this concept, a unit is RPA if a statistic of the RP within U exceeds a threshold:

$$\text{U is RPA if } \operatorname{stat}[RP(x): x \in U] > RV \quad (2)$$

Since the RP is a quantity independent on temporally variable anthropogenic factors, the status of an area as RPA does not change unless the RV is changed. For determining an appropriate threshold or RV of the RP one will link it to an exposure situation existing at a certain time, i.e. determine the RP threshold such that it corresponds to a threshold of indoor Rn. We shall call this linkage the *calibration* of the RP threshold. A method is explained below.

It must be emphasised that in the end any choice of a RP threshold is to some extent deliberate and subject to political and technical-procedural decisions. The more flexible tool to assessing geogenic Rn hazard is therefore, in my opinion, the RP map. Once a RP threshold has been established by linking the RP to indoor Rn concentration, the continuous RP map could be used to show the "degree of Rn-proneness" of an area.

### *2.3. The German radon database*

The German database "BURG"[3] contains geo-referenced values of indoor Rn concentrations, soil Rn concentrations and soil permeability from which the RP can be calculated. To the indoor values information on floor level, house type etc. is connected. The data have been compiled from several regional and national surveys. Via GIS, geological information can be associated to the locations, including a simplified geological classification proposed by Kemski *et al.*[8, 9], and based on analysis of dependence of soil Rn on geology. Soil Rn concentration and permeability were sampled according the Kemski protocol[10].

## 3. Estimation methods

### *3.1. Estimation of the radon potential*

The procedure is a geostatistical one and consists of several steps.

*Geological normalization*: Raw RP values, calculated according formula 1, are transformed $RP(x) \rightarrow Y := RP(x)/GM(RP; geo \ni x)$, where $GM(RP; geo \ni x)$ denotes the geometrical mean of the RP within the geological unit in which x lies. The transform is motivated by the right-skew, in fact nearly log-normal distribution of the RP. The GM is calculated from the data; it may be biased because samples have not been taken representatively over units, but this could not be corrected so far. The transform implies $E(\ln(Y)) \equiv 0$ which is useful because it supplies a population mean of the transformed data, which is required for simple kriging. In this method, geology plays the role of "external drift"; in the Rn mapping context this has been further discussed in[11].

*Normal score transform* (shortly nscore) of the Y: data $y \rightarrow \upsilon$ and test of multi-normality. This is a condition for simple multigaussian kriging (SMK) and sequential Gaussian simulation (SGS). These techniques allow interval estimates, i.e. estimating the local conditional distribution of the target quantity. Since ln(Y) is almost normal, the strict normalization may be replaced by log-transform.

*Interpolation of Y*: Possible by SMK, but preferentially SGS is used here. An alternative is direct sequential simulation (DSSIM), see[12], where also further references are quoted. We performed simulation with SGeMS (Stanford Geostatistical Modeling Software)[12]. 100 realizations were generated. Cell size is 10 km × 10 km.

*Back transform*: The simulated $\upsilon^*$ must be transformed back into Y space and then into the original RP space. See also section *3.4*.

*Variograms* were generated and modelled with Surfer v.8 software, which was also used for gridding and plotting. For the nscore transformed data a variogram model consisting of 60% nugget and two spherical components (12% with range 4.5 km; 28% with range 30 km) proved adequate, though a combination of exponential models performs similarly. Anisotropy was not considered. It can however be expected that regional anisotropy exists resulting from directionality of geological structures. The search radius for kriging was not restricted.

### *3.2. Probabilistic conditional estimation of indoor Rn*

Since the database of indoor Rn (C) is not sufficient for the purpose, a map of exceedance probabilities of the kind, $p(x) = prob(C(x) > RV)$ has been generated based on predictions from the RP. The method, which is quite complex and shall not be explained here in detail (see[13, 14]), constructs a model (called copula) of the joint probability distributions of the variables RP and C and calculates the wanted statistics from the conditional distributions. This leads to indoor Rn risk maps by plotting the conditional $p(x) = prob(C(x) > RV | RP(x))$. In principle, thresholds of the RP calibrated by thresholds of C could be determined that way. However, the method described in section *3.3* is much simpler and therefore preferred.

[3] A German acronym, "Bundeseinheitliche Datei Radon in Gebäuden", or Unified federal data file of radon in buildings (although it contains also soil Rn and geology data). The database is not publicly accessible.

*3.3. Estimation of geogenic radon prone areas*

A simple way to calibrate a threshold of the RP through a threshold or RV of indoor Rn (C) has been described in[15, 16]. The technique is binary classification evaluated with a technique known as receiver operating characteristics (ROC).

The 10 km × 10 km cells are first classified by a criterion CRIT based on a statistic of indoor Rn; for example $E_{cell}[C]>100$ Bq/m² (this has been used for the map shown in the results section, Figure 3) or prob[$C>100$ Bq/m³] $>0.1$, or the like. The criterion is in the end a political decision. The statistic is estimated from the empirical values (which introduces uncertainty into the result).

The same cells are then classified according a threshold rp of the RP, for which the cell estimates obtained by the method described in section *3.1* were used. Coincidence and disagreement of the two classifications is summarized in a truth table that quantifies the performance of the predictor rp with respect to the "truth", represented by CRIT. The performance is quantified in the ROC graphs in which the true positive rate TPR, defined as true positives / observed positives, is plotted against the false positive rate, FPR= false positives / observed negatives. The graph, technical details of the method and further discussions are given in[15]. Each choice of rp corresponds a point in the ROC graph. Varying rp results in concave (downward bent) line. After a certain score (a deliberate choice as several have been proposed in literature, some discussed in[15, 16]) the optimal point of the graph, corresponding to threshold $RP_0 = rp^{opt}$ is determined. This is the one which best divides the range of RP into two classes, which correspond to the division by CRIT. The optimal point is, essentially, the one farthest away from the diagonal (which indicates no relation) or closest to the upper-left corner, which denotes TPR = 1 and FRP = 0. Clearly, as the physical and hence statistical correlation between indoor Rn and RP is not perfect, such most optimal point cannot be found reality. The threshold $RP_0$ could be called conditional threshold, conditioned by the criterion CRIT. In this sense, this is the simplified version of the full model of dependence between C and RP, described in section *3.2*.

By fine-tuning the score, which determines which point on the ROC graph is optimal, one can set different relative importance of classification errors of first and second kind. First kind error means erroneous attribution of a cell as RPA by the predictor rp, or false alarm, while second kind error means erroneous designation of a cell as non-RPA, while in reality it is.

*3.4. Auxiliary procedures*

*De-clustering* serves for estimating unbiased means and other statistics like histograms. If clustered data are used, biases due to preferential sampling (represented by the clusters) can occur. Here, de-clustering has been performed laying a quadratic grid of given mesh and random offset over the data and retaining a random sample from each cell. The empirical distribution and wanted statistics of these data are calculated. This is repeated many times (100 chosen here) and means over realizations are calculated. The optimal grid size is defined as the minimum one above which the means remain approximately constant. (There are also other de-clustering techniques.) The histogram that is needed as input for sequential simulation should be estimated from the de-clustered data; so far, it has been done from the original ones.

*Nscore transform*, addressed in section *3.1*: $\upsilon := \Phi^{-1}(F_Y(y))$, with $\Phi$ the standard normal distribution. The transform can be performed e.g. in Excel. For back transform, it is stored as table. Back transform is done by linear interpolation $\upsilon \rightarrow y$ or $\Phi(\upsilon) \rightarrow y$. The multi-Gaussian property is difficult to check; for bi-normality, Emery's[17] procedure based on order variograms was used.

*Distribution tail modelling*: The simulated normalized values have to be projected back into Y-space. Since a simulated value may be above the highest or below the lowest empirical value, a model for distribution tails must be applied. Here the empirical distribution is defined $F^{emp}(z_i) = [-.5 + \mathrm{rank}(z_i)]/\#\{z_i\}$, where $\#\{z_i\}$ denotes the number of data or cardinality of the dataset. The upper tail is modelled by regressing the extreme part of the log-survival plot log (1-F) vs. log (z). The actual choice of the model is to some extent deliberate. The slope is called hyperbolic exponent and one models the upper tail as $(1-F(z))/(1-F(z_{upper})) = (z/z_{upper})^{-h}$ for $z>z_{upper}$, with $z_{upper}$ – the value where the tail starts.

## 4. Results and Discussion

*4.1. Summary statistics of the RP and indoor Rn*

The data are spatially clustered; this applies to the locations of the indoor data even more strongly than for the ones of the RP data. Furthermore they have not been sampled representatively with respect to a target value referring to Germany as a whole (possibly so regionally). Therefore, statistics of the raw values are biased estimators of quantities over the countrywide population. Spatial means (and other related statistics) can be estimated (1) by de-clustering the data and calculating them from the de-clustered data, and (2) by spatial interpolation over the entire domain and calculating the statistics from the interpolated data.

These techniques lead to the spatial mean of indoor Rn, but these are different from means over buildings or persons, because these are not uniformly distributed over the territory. A demographically weighted mean which is the relevant quantity for exposure requires data about

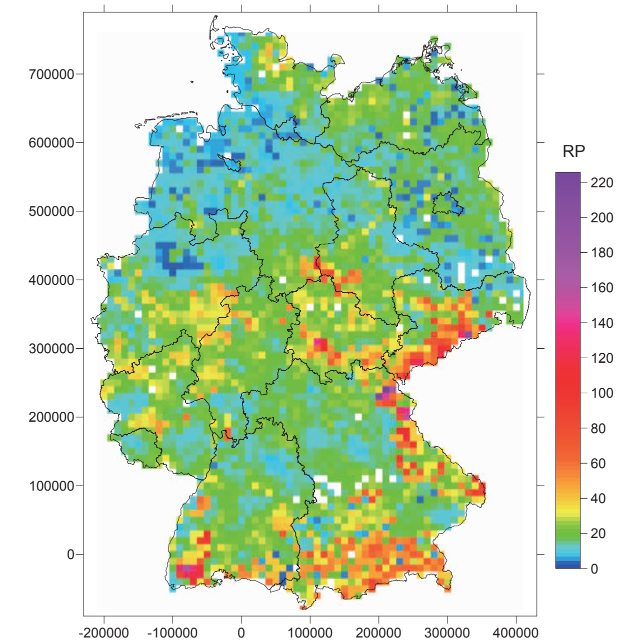


**Fig. 1.** Estimated expectation of the radon potential over Germany, based on 100 realizations of sequential Gaussian simulation. Coordinates: projected (Lambert azimuthal equal area), units: m. Cell size: 10 km × 10 km.

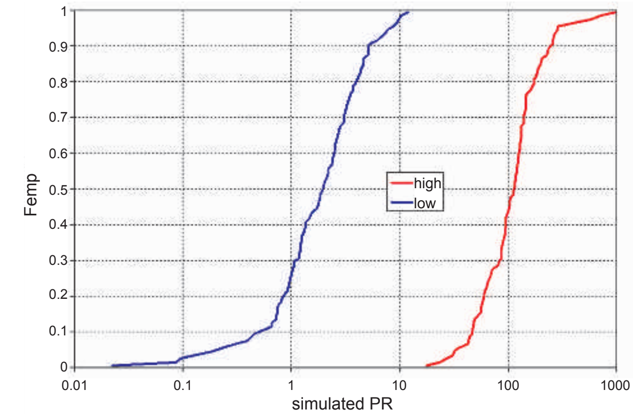


**Fig. 2.** Estimated conditional cumulative distributions (ccdf) at one high and one low-RP location. Femp – the empirical cumulative distribution of the 100 realizations corresponding the simulation algorithm.

demographic distributions (population density, distribution of buildings per type), which we do not have at present. Therefore, the spatial mean is used as (probably biased) surrogate until the required data are available.

3745 values of the RP are available and 15,563 of indoor Rn concentration of living rooms in ground floors of buildings with basement. This sub-set was chosen in order to obtain a more homogeneous dataset. The following statistics have been derived from de-clustered data.

The arithmetic mean (AM) of the RP over Germany equals about 22 (variability 140%), its geometric mean and geometric standard deviation, GM = 12 and GSD = 3.3.

The AM of indoor Rn concentration (ground floor, buildings with basement) equals 45 Bq/m$^3$, variability 116%, GM = 36 Bq/m$^3$, GSD = 1.8. The estimates from de-clustering and from the transfer model (mean over all conditional means) coincide up to a few percent. The AM for Germany derived from the database of the European Indoor Rn map (latest status in[18]; based on AMs over 10 km × 10 km cells), equals 68 Bq/m$^3$ (ground floor rooms, but including buildings without basement; 1887 cells comprising 26,036 data, compared to 15,563 used for the analysis presented here).

### *4.2. The RP map*

The RP map of Germany, which results from the procedure described in section 3.1, is shown in Figure 1. Figure 2 shows two examples of local conditional cumulative distributions (ccdf) at one high and one low RP location. From these graphs the local statistics of the RP are derived, such as the so-called E-type estimate, which is the mean computed from the ccdf, $E[RP] = \int rp \; d(ccdf(rp))$. This mean is the quantity plotted in Figure 1 Blank pixels are ones to whose centre no geology could be attributed which is calibrated by empirical RP values.

The map essentially reflects the geology of Germany, with high RP areas in granite regions of the Erzgebirge and the Bavarian Forest (Centre-East) and the Black Forest (South-West), Rhyolite of the Thuringian Forest (about 100000/300000), Alpine sediments in South Bavaria (Southern border) and certain glacial sediments in the North.

### *4.3. Maps of radon prone areas*

A map of radon prone areas defined by the RP threshold $RP_0 = 32$ is shown in Figure 3. This threshold corresponds to the threshold $C_0$ of indoor Rn: mean within 10 km × 10 km cells to be greater than 100 Bq/m$^3$; this is the criterion CRIT, which calibrates $RP_0$. The frequently used, so-called Y-score was used for determining the optimal point in the ROC graph (for discussions and literature see[15]; Do not confuse the commonly denoted "Y-score" statistic with the transformed variable Y). First and second kind classification errors were set as equally important.

Due to the approximately spatially log-normal distribution of C with GSD ≈ 1.91, the CRIT: $E[C] > 100$ corresponds to $prob(C > 100 \text{ Bq/m}^3) \approx 38\%$ which is about 8.4 times the probability for the whole of Germany (4.5%). Further it corresponds to $prob(C > 300 \text{ Bq/m}^3) \approx 1.8\%$, which is 5 times the probability for Germany (0.36%).

This means that $RP_0 = 32$, which is the RV for the RP according formula (2), corresponds to $\alpha = 5$ and RV = 300 Bq/m$^3$ for indoor Rn according formula (1). 300 Bq/m$^3$ is the highest RV permitted in the new European Basic Safety Standards (EU-BSS[4]).

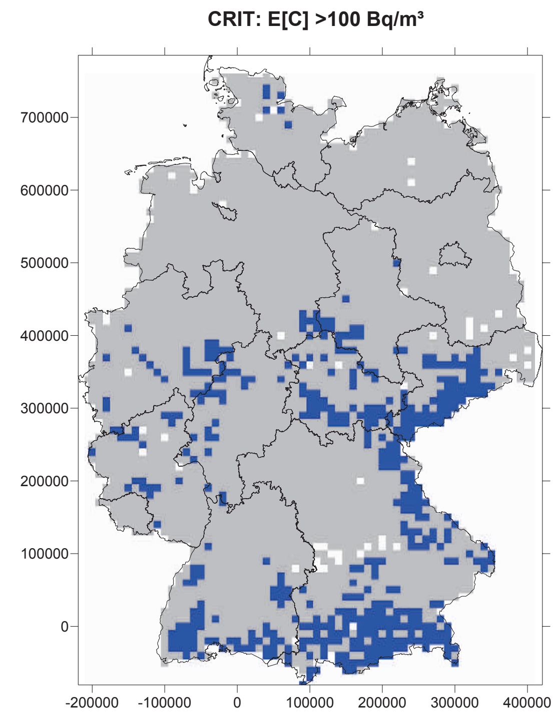


**Fig. 3.** Radon prone areas defined by threshold rpopt=32 derived from criterion CRIT. Dark (blue) shaded: RPA, light grey: non-RPA; white: missing predictor data. Coordinates as in figure 1.

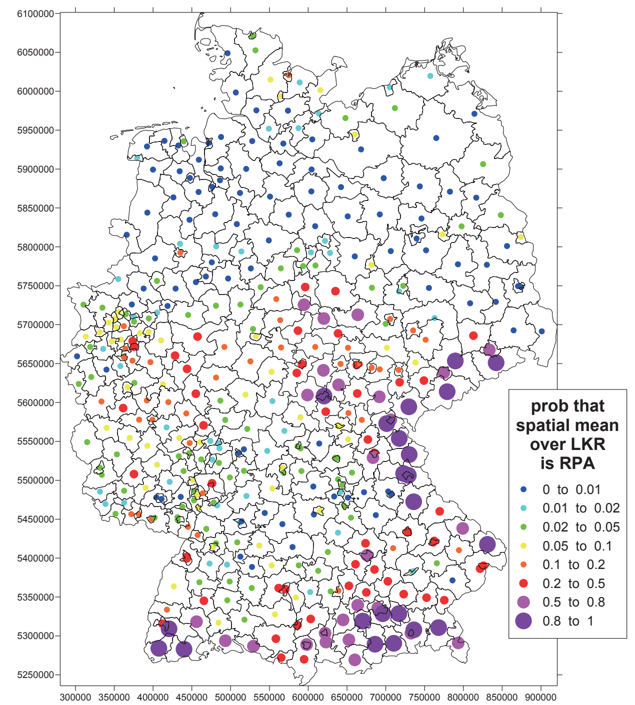


**Fig. 4.** Probabilities that the spatial mean of the RP exceeds 32 for the German districts (Landkreise = LKR). Coordinates: Projected German system, units: m.

The value $RP_0$ = 32 is quite close to the value 35 which Neznal[6] (section 2.5.1) propose as threshold for defining a RPA, based however on different reasoning.

$RP_0$ = 32 implies that about 13% of the German territory are affected. For administrative reasons RPAs should be defined on administrative units rather than based on grid cells. While the target is attributing RPA status to municipalities, data resolution has so far only allowed doing it on district level ("Landkreis" = NUTS 3 level[4], 402 units). In about 14% of the districts the estimated spatial mean (over the district) RP is above 32; in about 24% of all districts, in more than 10% of their area the RP is above 32. Including demographic data, about 12% of the population live in districts with mean RP>32. The map, Figure 4, shows the probabilities per district that the spatial mean of the RP exceeds 32. This map can be understood as one, which shows the "degree of Rn-proneness" for the districts.

## 5. Summary and Future work

In this article, it was shown how a radon potential map has been constructed and how geogenic radon prone areas were estimated. The procedures are relatively complex and therefore only the outlines could be presented. The results are used in the current discussion about translation of the European BSS into a national radon action plan.

The procedure involves a number of political decisions, such as, which reference values to use, or which relative importance to assign to first and second kind errors. Further deliberate decision are technical ones, such as, which definition of the RP to adopt, which de-clustering technique to use, etc.

There is a number of technical improvements to be tackled. Geological classification is still not optimal, in our view. Certain distinct geological units could probably be merged; others may have to be divided into separate one in order to better reflect their role as predictors of the RP. Technicalities such as histogram estimate and distribution tail modelling should be refined. Establishing a comprehensive uncertainty budget is difficult because of the many steps in the procedure. Propagation of uncertainties through these steps is complicated, but sometimes even the "elementary" uncertainty induced by one particular modelling step is difficult to quantify. Probably this is possible only through extensive simulations. In addition, validation is a problem, because the database is insufficient for classical procedures like data partition, in most cases. Exceedance probabilities for

[4] NUTS = acronym of French „Nomenclature des unités territoriales statistiques", or European Nomenclature of Units for Territorial Statistics. See e.g. http://en.wikipedia.org/wiki/Nomenclature_of_Territorial_Units_for_Statistics or http://ec.europa.eu/eurostat/en/web/products-manuals-and-guidelines/-/KS-BD-03-002-3A-PART2 (both accessed 28.4.2015)

high thresholds are anyway difficult to validate because of lack of data. Where possible, simple procedures such as analysis of residuals or leave-one-out cross-validation was performed. Altogether, although the models are already quite developed, quite a bit of legwork and fine-tuning is still to be done.

It must also be said that the German indoor Rn database is not sufficient for achieving an accurate assessment of exposure, neither of its countrywide mean, nor of its geographical structure. The data are highly clustered, as they stem from different regional projects with partly different purposes. Representativeness is questionable (at the same time it can be assumed that the individual values themselves are correct). On the other hand, the soil Rn database is more reliable, which is why the RP is preferred for assessing also statistics of indoor Rn; however, the price to pay is a considerable modelling effort. Still, indoor Rn data are needed for calibrating thresholds of the RP, as demonstrated in this article. Therefore, it may be that further – and altogether better quality assured, as survey design is concerned – indoor Rn data will lead to somewhat different conclusions.

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