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OPEN PROBLEMS IN RADON RESEARCH

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Abstract. *In spite of decades of scientific research about radon, which has resulted in an immense corpus of literature and deep knowledge about all aspects of radon physics, its behaviour in the environment, its measurement and its dangers and benefits, many technical challenges remain. In course of increasingly strict regulation, new challenges emerged, mostly related to quality assured decision making in radon abatement policy and to application of advanced statistical methodology. In this paper, we give an overview about a number of topics of radon research, whose discussion and deeper investigation we find, at the one hand, important for the sake of implementing efficient radon abatement policy and interesting scientifically, on the other, as they elucidate the complexity of environmental systems up to their interaction with society in a paradigmatic manner.*

Keywords: *Environmental and indoor radon, estimation and statistics, quality assurance, radon regulation, radon as tracer*

1. INTRODUCTION

Environmental radon (Rn[1]) has been given increasing attention in Europe, primarily due to its radiological significance, e.g. [1], but also its potential as tracer of ecological processes. The former motivated regulation, latest the European Basic Safety Standards Directive, 2013 [2], here referred to as EU-BSS. EU Member States must transpose the Directive into National Law. Among other, it requires them to establish National Radon Action Plans whose objective is reduction of Rn exposure. Also some non-EU countries have adopted similar schemes or the similar IAEA-BSS [3].

During BSS implementation certain challenges emerged. Fulfilling the action plan means (i) defining appropriate action and (ii) depending on Rn exposure and additional possibly constraining conditions (see section 2.3c), deciding about action aimed to establish or verify compliance with law. A decision must be quality assured (QAed) in the sense of being reliable. Hence the steps leading to a decision must be QAed. Reliable means that the probability of erroneous decision be acceptably low. For Rn (and Tn), this concerns QA of survey design, of measurement and of models which underlie e.g. estimation of Rn priority areas (RPA) or of doses. We therefore speak of a QA chain, the links of which must be QAed.

Some challenges were addressed in the Empir project MetroRADON (2017-20) [4]. Among topics were precise determination of low indoor Rn concentration (low meaning in the order of 100 Bq/m^3), influence of Tn on Rn measurement and estimation of RPAs. However, issues remained open because of the limited capacity of that project. Some are addressed here as an incentive for further research.

The paper is organized as follows. In section 2, we present a list of topics which we think deserve further study. In section 3, two selected technical topics related to Rn mapping will be discussed in somewhat more detail, without however being able to provide an exhaustive overview, given limited space. Therefore, we also refrain from attempting exhausting referencing, since enormous amounts of Rn related literature exist.

2. RESEARCH TOPICS

For the sake of clearer structuring, we divide the topics into four groups: (1) issues related to measurement and data acquisition; (2) modelling, prediction and estimation, mapping and statistical issues; (3) matters related to regulation, decision QA and Rn abatement policy; (4) environmental Rn as tracer. - The list is certainly not complete.

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[1] Here 'Rn' denotes the isotope ^{222}Rn. For ^{220}Rn, we use the term thoron (Tn).

2.1. Radon data acquisition

(a) Radon surveys. Rn data should be representative for the area (or period of time) which they should characterize. Representative means that the statistical distribution of a sample (i.e. the set of measurements, observations or data) is equal to the one of the true quantity, from which the sample is a "draw". Deviation from representativeness can lead to bias. Generating representative samples and verifying representativeness is not trivial and should be given more attention as part of the QA chain. Lack of representativeness can, to some extent, be compensated by modelling, but every model inevitably induces additional uncertainty. Putting it more general, one must clearly distinguish between intrinsic data uncertainty, i.e. uncertainty of individual values due to measurement error and deviation from measurement protocol, and uncertainty of the sample (i.e. set of data), due to deviation from representativeness.

A second, increasingly difficult matter is data protection and privacy concerns. IRC data are sensitive and by georeferencing – which is necessary for statistical evaluation and mapping – individual buildings can be identified which violates data protection law, in particular the recent EU's General Data Protection Regulation (GDPR). In strict interpretation, even storing existing georeferenced data may become problematic.

(b) Real vs. laboratory environment. In real environments Rn concentration often fluctuate strongly, as do environmental conditions (humidity, temperature, vibrations, etc.). Performance of Rn measurement instruments must be assured under these conditions, which may be more demanding than under controlled stable laboratory conditions, as has been shown in the MetroRADON project. Active monitors which are nowadays quite cheap, should be subjected to QA more thoroughly, as they will play an increasingly important role in Rn surveying.

(c) Thoron surveys. In most cases, dose from Tn and progeny plays a minor role compared to Rn. Since its half live is very short, 56 s, and consequently its diffusion length in air, about 3 cm (compared to 3.7 days and about 2.3 m, respectively, for Rn), it cannot travel very far by diffusion and therefore its concentrations are highest near the source. Most importantly, this is building material. Depending on contribution of advective or turbulent transport, it can reach also longer distances. On the other hand, its progeny have comparatively long half life and distribute more or less uniformly in rooms, similarly to the ones of Rn. Regional prevalence of "Tn-prone" building material is little known except from a few studies (China, Balkans). Simple passive Tn measurement similar to Rn is possible, but QA is more demanding and procedures are disputed. Due to its source distance dependence, reproducible measurement of Tn concentration is not trivial and no generally accepted protocols seem to exist. Further studies are necessary.

(d) Radon and thoron progeny. Exposure and dose are mostly generated not by Rn and Tn gas but by their progeny. Measurement of their long-term means is more difficult than the ones of Rn and Tn. Therefore, dose assessment is commonly done using models (supposing generic equilibrium factors) which introduces additional uncertainty. Passive measurement methods of Rn and Tn progeny have been proposed (latest: [5], see references there), but have not yet been found wider acceptance apparently due to QA concerns. Development should be advanced in dedicated projects.

(e) Workplaces and dwellings. Regulations of the BSS concern workplaces more than dwellings, regarding obligatory measurement in RPAs and other action. On the other hand, most data which underlie maps and form decision bases, are from surveys performed in dwellings. Rn characteristics of workplaces and dwellings are different, so that a decision valid for one type may not be applicable to another. This may impair credibility and acceptance by stakeholders and even lead to legal challenge. In particular, this concerns "big" buildings (Some results have been found in the Big Buildings project, [6]), which may have special Rn characteristics. Further, a widely accepted typology of workplaces regarding Rn is still missing, as are protocols for Rn assessment on workplaces. The problem of different Rn characteristics in dwellings and workplaces has also been addressed in MetroRADON and in a recent paper [7].

2.2. Modelling, statistics, mapping

(a) Temporal variability. In particular indoor Rn concentration (IRC) varies strongly over time. Although variation is periodic in most cases with diurnal and seasonal cycles, their amplitudes vary and they are superimposed by non-periodic variability owing to meteorological episodes and human usage and behaviour. Since reference levels (RL) as stipulated in the BSS pertain to long-term means, Rn concentration must be measured over periods long enough to allow estimation of the long-term mean. Usually, "long-term" is understood as 1 year, although it is known that also annual means can vary for up to 20%. (Whether there is a long-term trend perhaps due to climatic change, apart from random fluctuation, is a matter of ongoing debate. For example, higher or lower humidity may induce secular change of geogenic Rn potential, leading to different infiltration rate into buildings.) A theoretical alternative is modelling the mean from short-term observation, but this requires good knowledge of the physical properties of a building and of site-specific meteorological dynamic, which is usually not available. In any case, temporal Rn variability entails the problem of testing compliance of Rn concentration representing a limited measurement period with a RL [8].

Related to the previous, RPAs which are cornerstones of Rn Action Plans in the EU, due to EU-BSS art. 103/3, are commonly estimated either from measured IRC directly or via models calibrated by measured IRC. Therefore, uncertainty of IRC, in particular the one induced by temporal variability, propagates into RPA estimates. This uncertainty component has not yet been investigated to our knowledge.

(b) Extremes. In most cases, Rn concentrations, in particular IRC, are right-skew distributed within aggregation units, often about log-normally. Typical geometric standard deviation (GSD) of IRC within 10km × 10km cells is about 2. This implies rare occurrence of very high values which lead to high exposure and consequently risk. This must be given special attention for radioprotection reasons. Identification and modelling of rare events are practical and mathematical challenges (practical: because dense surveys are necessary, or good knowledge of conditions which lead to high IRC; mathematical: involving spatial extreme value theory), as is the question how to deal with them in the framework of the priority concept of the BSS.

(c) Predictors. Conclusions about a local Rn situation (local mean IRC or probability to exceed a RL) are often drawn from geogenic quantities, usually taken from databases such as base rock, soil and tectonic maps, climatic charts etc.. Increasingly, large national and Europe-wide databases of geogenic quantities are available and freely accessible, and GIS methods are more and more common to process the data. Various methods of relating geogenic to indoor Rn have been developed, some technically demanding (see sections 3.1f.).

However, usually the models suppose natural conditions and little is known on the effect of urbanisation on this assumption.

(d) Mapping. Rn mapping is quite advanced in Europe, but it remains an active field of research and development. Methods range from simple aggregation of values into cells (e.g. the European IRC map [9]) to geostatistics (local regression, kriging family, and other) and most recently advanced regression by machine learning (see section 3.1).

Different objectives are served by different mapping approaches: isopleth maps show continuous levels of the mapped quantity, choropleth maps, values per unit of interest (country, municipality) and class maps, delineation of areas according a decision rule. The latter are used for displaying RPAs. Given the sensitive nature of RPA delineation (section 2.3a), QA of such maps is especially important, but relatively little developed. This concerns estimation of probabilities of erroneously labelling an area RPA or non-RPA, which may have economically and legally expensive consequences.

2.3. Aspects of Rn abatement policy

(a) Decision QA. Formally, a decision can be understood as classification. From a set of options, one is selected based on criteria and arguments. For example, a municipality is classified RPA if the probability that IRC exceeds the RL, exceeds a probability threshold, e.g., prob(IRC>300 Bq/m^3)>10%. Whether the condition is fulfilled, depends on data (which are limited, maybe not representative and have uncertainty) and models (if necessary in the procedure) may be uncertain. Hence the decision is uncertain to an extent. An area may have been labelled RPA erroneously because it is none (1st kind error, “false alarm”) or non-RPA erroneously, because it is one (2nd kind error, “falsely omitted alarm”). The probabilities of such errors, which are the analogues of confidence intervals of estimated means of continuous quantities, should be estimated as part of decision QA. A reliable decision is characterized by high specificity (low 1st kind error probability) and high sensitivity (low 2nd kind error probability).(The matter has also been discussed in MetroRADON.)

(b) Hazard and risk. Hazard is potential risk. Hazard exists also in a location where there is nobody whose wellbeing can be harmed. (More generally, no good or value which can be impaired.) Reversely, in order that hazard becomes risk, somebody must be affected or concerned: factors of “concernment” consist of vulnerability (conditions that enable exposure) and exposure (presence of persons). The common definitions of RPA mean an area in which (i) the probability of IRC exceeds the RL, exceeds a percentage, or (ii) mean IRC exceeds a RL or (iii) certain geogenic conditions are fulfilled, e.g. certain geological base etc. (independently of actually observed IRC). These definitions rely on the hazard aspect, but not on risk, because they are independent of concernment (number of persons exposed). This means that this RPA concept may reduce individual risk (which is in average higher in such areas), but not the collective risk, measured as total detriment (number of lung cancers), which is proportional to the collective, i.e. the sum of individual exposures. If the objective of Rn abatement policy is reduction of the detriment (EU-BSS Annex XVIII/13, also IAEA Fundamental Safety Principles [10] (Principle 7)), the common RPA concept is little effective and Rn policy should be adapted. Discussion about how to implement the risk, in addition to the hazard aspect, into regulatory frameworks more efficiently is currently ongoing; more details in [11,12].

(c) Weighing between societal factors and the role of stakeholders. Criteria and arguments which determine decision about certain action in the framework of Rn Action Plans are not only Rn exposure, but also constraints from the economical or political sphere. Evidently, the stricter criteria derived from dose assessment (lower RL, larger RPA), the higher the costs and likelier resistance of stakeholders who are mainly concerned. The question how to weigh conflicting stakeholder interests does not belong to the sphere of physics, but to political science; nevertheless it is crucial and should be given more attention. Currently, public discussion about it is nearly inexistent and stakeholder interests assert themselves through political and economical power, which appears little satisfying from a democratic perspective.

(d) Radon awareness. Related is the question of how to increase public awareness towards the problem of Rn risk. Among factors may be that detriment due to Rn is not readily visible like sudden natural disasters; that it is difficult to hold somebody responsible for the presence of Rn; its ambiguous nature of being of natural origin on the one hand, but its actual concentration anthropogenic controlled; and that prevention and remediation require personal initiative to some extent, including costs (depending on subsidies, if there are any). Also this matter has been addressed in MetroRADON.

(e) Radon and Citizen Science. Again related to the last topic, the case of protection against Rn exposure may be supported by involving citizens to a greater extent, instead of just prescribing regulation. Citizen Science (SC) schemes could consist in giving people the technical possibility to acquire, collect, evaluate and discuss Rn data by establishing appropriate platforms. A pilot project is [13,14]. The subject is also part of the ongoing RadoNORM project [15,16]. A SC project in which the aspect of data acquisition has been realized very successfully is Safecast [17].

2.4. Radon as environmental tracer

This group of topics shall be mentioned only shortly. The behaviour of Rn and Tn (and progeny) in the environment depends not only on their physical properties, but also on the ones of its environment. Therefore, studying Rn can also elucidate environmental processes. The reader is referred to the rather comprehensive book [18]. Here, we mention only one topic.

Radon as seismic indicator. (The following text has been partly excerpted from [19].) Rn and Tn concentrations in geogenic environments react sensitively to changes of their physical-chemical state (as do other geogenic gases such as CO_2, CH_4 and He). This has been known for long and numerous respective results have been reported for Rn in rock, soil, groundwater, outdoor and indoor atmosphere. Also seismic signals have been identified, either indicating tectonic phenomena preceding earthquakes, or reactions to them as manifest in change of Rn exhalation. The physical reason is seen in that tectonic stress which eventually discharges in earthquakes leads to alteration of transport properties of the ground (porosity, tortuosity, permeability, water content), in turn changing gas emission rates. It is therefore obvious that it has been studied whether the analysis of Rn time series could allow earthquake prediction. However, in spite of much effort, and although the effect does exist, it has so far not been possible to exploit is for reliable prediction. This means predicting the occurrence of an earthquake exceeding certain magnitude, or its probability, in an area and in a certain period of time with acceptably low error probability; this would be the condition for practical usability, i.e. decision whether certain protective action is necessary, such as evacuation in extreme cases.

Methodically, time series of Rn (possibly synchronously with other geogenic gases and other environmental, notably meteorological quantities which predominantly control Rn dynamics) are analyzed and signals identified which can be related to tectonic phenomena. Even if the target, i.e. earthquake prediction, has not yet been achieved, the studies have led to better understanding of Rn dynamic and geogenic processes which control it.

3. SELECTED TOPICS

3.1. Machine learning methods in Rn mapping

Geogenic Rn concentration (now always talking about temporal mean) at a location, or its mean or exceedance probability in an area, depends on various geogenic factors: geochemistry, lithology, soil properties (texture, permeability etc), hydrology, tectonics (presence of faults), topography, climate. IRC depends, in addition, on anthropogenic factors, such as building properties and behaviour of inhabitants and users. (The impact of anthropogenic alteration of the ground and urbanisation may be counted among geogenic and anthropogenic factors.) Some factors are physically directly linked to Rn, e.g. uranium content in the ground which is the parent nuclide of Rn (thorium the one of of Tn) and therefore ultimately its source. Others are proxies of difficult to observe processes, typically transport. The relations between these quantities and factors are very complex (see the “rock to risk” scheme in [9], p.110) although the underlying physical laws are simple (radioactive decay, diffusion, advection, sorption).

Estimating target variables, such as the geogenic Rn potential GRP (which essentially quantifies Rn availability at the surface and for infiltration into buildings) or the IRC, from intricately interwoven controlling factors is a technical challenge. It has turned out that traditional (multiple) regression schemes perform sub-optimally. On the other hand, advanced regression methods, notably based on machine learning (ML), have shown better results if dealing with high dimensional predictor spaces. They do not require prior definition of regression models. Among these are artificial neuronal networks and classification / regression trees. The latter have been used successfully for predicting the GRP from multiple, interdependent continuous and categorical quantities, [20,21]. In this approach, local estimate of the target variable is the expectation of the regression model at a location.

A special class of regression relies on local observations of the target variable in the first place. This is the field of geostatistics, which exploits analytical properties of observations which are understood as “draws” from a particular realization of a stochastic process (for the GRP, e.g. [22]). In principle, supporting covariates can be included (cokriging, cosimulation), but this option is limited in practice and does not allow high dimensional settings. Pre-processing by dimensional reduction (e.g. by PCA or similar) is an option, but has rarely been applied in this context, to our knowledge.

Thus, advantages of ML are that no model must be specified and that it is very well suited for managing high-dimensional predictors. The disadvantage is that data of target variables serve only for model calibration, but local deviation of data from the resulting model is not honoured but left as residual error. Reasons of deviation may be data (measurement, protocol) error, but also that locally the predictors are not sufficient to capture the behaviour of the target variable. On the contrary, geostatistics has the advantage to honour local behaviour, but can still lead to local misestimation: (i) in the presence of regionally correlated observation error and (ii) in the vicinity of anomalies, defined as instances which are structurally different from their neighbours, because they violate analytical assumptions of geostatistics (2nd order stationarity; practically, that at an anomaly, spatial correlation length is different from the “background”).

The methods can be combined, leading to various versions of regression kriging. Dealing with local effects is however still challenging and methodical development is an active field of research.

3.2. Relating IRC exceedance probability and RPA status to geogenic predictors

The common notion of RPA rests on the probability or frequency of buildings in which IRC exceeds the RL. (For a conceptual critique see 2.3b above.) The probability is classified according to a threshold (2.3a).

In some cases, IRC data are not sufficient, so that the probability – or the RPA status directly – have to be estimated from predictors. In Germany this is done by relating IRC to the GRP [20,21,22]. The exceedance probability can be estimated through logistic regression [21,23] and RPA status (which technically is a binary random variable) by cutting off at given probability threshold. An alternative could be estimating the full bivariate distribution (GRP, IRC) (or multivariate, for more predictors) and retrieving the wanted exceedance probability from the conditional distribution; this has however turned out technically rather complicated [24].

If only the RPA status is wanted, one may bypass estimation of the exceedance probability. This could again be done by ML, in this case not in regression but classification mode. Its potential still remains to be explored. An alternative, simple and robust method is optimizing cross-tabulation between classified observed exceedance probability and predictor (GRP or other), leading to a derived threshold of the predictor upon which RPA delineation is finally based. Optimization may be done through the ROC (receiver operating characteristic) method, e.g. [25] (which can in fact be understood as a simple ML technique). The method has the additional benefit that classification error (needed for assessing decision reliability, section 2.3a) is a direct output. However, the technique cannot deal with multiple predictors. Also multinomial classification (if more than two hazard classes are envisaged, such as a "low-medium-high" scheme) does not appear straight forward.

A drawback of common logistic regression as well as of the cross-classification approach is that calibration is done via classified IRC, so that its actual value is not honoured, but only whether it exceeds a threshold or not. To which degree this leads to a bias in resulting maps remains to be investigated.

4. CONCLUSION

While decades of radon research have led to an immense corpus of scientific literature and essential knowledge of how to measure Rn, its spatial and temporal variability, and how to deal with it in regulatory frameworks, it appears that a number of questions still remain open – or indeed have emerged only during these advances. In particular, this concerns statistical techniques and matters of QA. Awareness of QA has increased generally, but in particular it is being taken more seriously in view of economic cost of Rn policy and the necessity of decisions being legally proof.

In this article, we addressed a number of pending Rn issues without being able to go into very detail; instead, the paper is intended as an incentive for further research. We hope that some ideas are being taken up by the community.

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