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Spatial association between residential radon concentration and bedrock types in New Hampshire

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Abstract Using a large database of residential short-term radon measurements in New Hampshire, this study evaluated the ability of expert-assigned bedrock radon potential for predicting residential radon concentration. First, each bedrock type was assigned a radon potential level by a geologist familiar with the local geology. Then, using residential radon measurements, a continuous surface of radon concentration was generated through a kriging process. The mean residential radon concentration within the spatial extent of each bedrock type was then calculated based on that surface. The Spearman Rank Correlation Coefficient was calculated between the two ranks of the bedrock types, one based on the expert-assigned potential level and the other based on the mean residential concentration. A strong correlation between the rank correlation and the area of the bedrock type was found. When only the 15 largest bedrock types were used, the Spearman Correlation Coefficient reached 0.6. Geological knowledge is concluded to be useful in predicting and mapping residential radon concentration, but the prediction should be interpreted with caution, especially for areas in which the underlying bedrocks are highly localized.

Keywords Bedrock · Residential radon · Kriging · Spearman Correlation · New Hampshire

Introduction

Local bedrock is an important source of radon gas in dwellings (Cui 1990; Hudak 1996; Kemski et al. 1996, 2001, 2005; Morland et al. 1998; Apte et al. 1999; Quindós Poncela et al. 2004; Sundal et al. 2004a, b). Bedrock geology is a primary factor used by the US Geological Survey (USGS) and the US Environmental Protection Agency in assessing and mapping indoor radon potential (Gundersen and Schumann 1993, 1996). The British Geological Survey also uses geological units to summarize measured residential radon concentration values to produce radon potential maps (Miles and Ball 1996; Miles 1998; Miles and Appleton 2005). Such radon potential maps have been used in lung cancer research (e.g., Pearce and Boyle 2005).

Efforts have been made to verify the correlation between bedrock and residential radon concentration (e.g., Geiger and Barnes 1994; Gundersen and Schumann 1996; Apte et al. 1999; Sundal et al. 2004b). In most of these studies, however, the density of residential radon measurement samples is fairly low (usually several hundred per county), and the aggregation level is high (town or even county). In addition, almost all of these studies used descriptive statistics directly calculated from samples to perform further hypotheses tests, which may lead to biased inferences. First, for studies using voluntarily reported measurements, the measurements cannot be considered to be a random sample. Second, for many studies claiming that the samples were randomly or systematically randomly collected, the sampling strategies were only applied to houses, not to locations. Since houses are not randomly distributed in space, the samples are not random in space, either. Even with spatially random sampling, simple descriptive statistics can still be biased due to spatial autocorrelation. The theoretically ideal solution to this problem is a high-density systematic sampling strategy. Unfortunately, this is not only costly, but also impossible in most cases due to the likelihood of sample locations occurring at places where no residential houses exist. A geostatistical solution to this problem is to perform kriging interpolation and use the interpolated values to conduct further statistical analysis. This solution rarely has been adopted in radon-bedrock studies (Miles 1998), possibly due to the concern about nonstationarity in residential radon concentration values. Nonstationarity refers to the violation of the principle that the difference between two values is determined by the geographical distance between them. For example, two nearby houses share similar environments (geology, soil, groundwater, etc.) and should have similar radon concentration measurements, but in reality, the measurements can vary simply because the two houses have very different construction characteristics. Nonetheless, ignoring the spatial aspect of the sample is a more serious problem than nonstationarity. It is almost impossible that the spatial distribution of the sample happens to perfectly reflect the association between two features (e.g., residential radon concentration and bedrock type). In other words, the locations of samples may not be representative (Geiger and Barnes 1994), and the spatial autocorrelation may lead to unpredictable biases in the resulting statistics and make the comparison between residential radon measurements and bedrock radon potentials meaningless. The impact of nonstationarity can be estimated in kriging.

This analysis used a large database of short-term residential radon concentration measurements with relatively detailed location information and employed the kriging technique. The study area of this research is the State of New Hampshire, a region known for its granite bedrock. Particularly, this study tests to what extent expert knowledge of radon potentials of different bedrock types can be used in predicting and mapping residential radon concentration.

Data

Residential radon concentration

The dataset of residential radon concentration samples was provided by the Radon Program of the New Hampshire Department of Human and Health Service (DHHS). The dataset is an outcome of an ongoing radon survey program conducted by the state. Homeowners willing to participate in this program receive a charcoal canister test device from the state and voluntarily report the measurements back to the state. The test kits used in this program were designed to be exposed to the air for a period of 4–7 days (short-term test). The average concentration over the last 3 days of exposure is used as the value for the tested dwelling. The dataset used in this study contains 17,356 radon measurements taken from various types of dwellings across the state between 1987 and 2004. To control for location of test kit in a dwelling and for construction characteristics, only the 10,164 measurements (59% of the whole dataset) taken from the basements of single-family houses were used in this analysis. The measurements were predominantly done during the home heating season (November–April).

It has been reported that basement and winter measurements tend to give higher estimates for the "annual average radon concentration in the normal living area" than nonbasement and summer measurements (Apte et al. 1999; Chen 2003). However, some researchers have assumed that the relationships between the basement measurement and the overall house concentration and between the winter measurement and the annual concentration do not significantly vary. Thus the basement and winter measurements have the same spatial pattern as that of the annual average residential radon concentration in an area (Apte et al. 1999; Chen 2003). This is the assumption adopted in this study.

For privacy reasons, exact locations of the tested houses are not available for the current research. Instead, DHHS created a regular grid that covers the whole state and provided the information about which cell of the grid each measurement falls into. The cell size of this grid is 800 m on each side. A total of 4,661 out of 43,464 cells contain at least one measurement from the basement of a single-family house. Each of these 4,661 cells was used as a sample point in the kriging process. For a cell containing multiple measurements the geometric mean of these measurements was used as the value of that cell in the interpolation.

Bedrock radon potential

In 2002, the former State Geologist of New Hampshire, Eugene Boudette, was asked to classify the bedrock types in the state according to their radon potentials (i.e., the potential to emit radon gas). A seven-class system, where 1 indicates the highest level of radon potential and 7 indicates the lowest, was used. Then, without referring to any residential radon measurements, every bedrock type in the USGS geology map (Lyons et al. 1997) was assigned to one of the classes based on the genesis of the rock and its uranium composition (Fig. 1). This resulting potential map is largely consistent with the one created by Gundersen and Schumann (1993), but is much more detailed in terms of both bedrock classification and radon potential classification.

Methods

The kriging method was used to create a continuous surface of residential radon concentration covering the whole state. Before the kriging interpolation, a natural-base logarithmic transformation was applied to the cell values, which considerably reduced the bias and uncertainty in the resulting surface. Geostatistical Analyst® of ArcGIS® was the tool used to perform the kriging interpolation. To search for an optimal parameter setting, about one thousand experiments were performed.

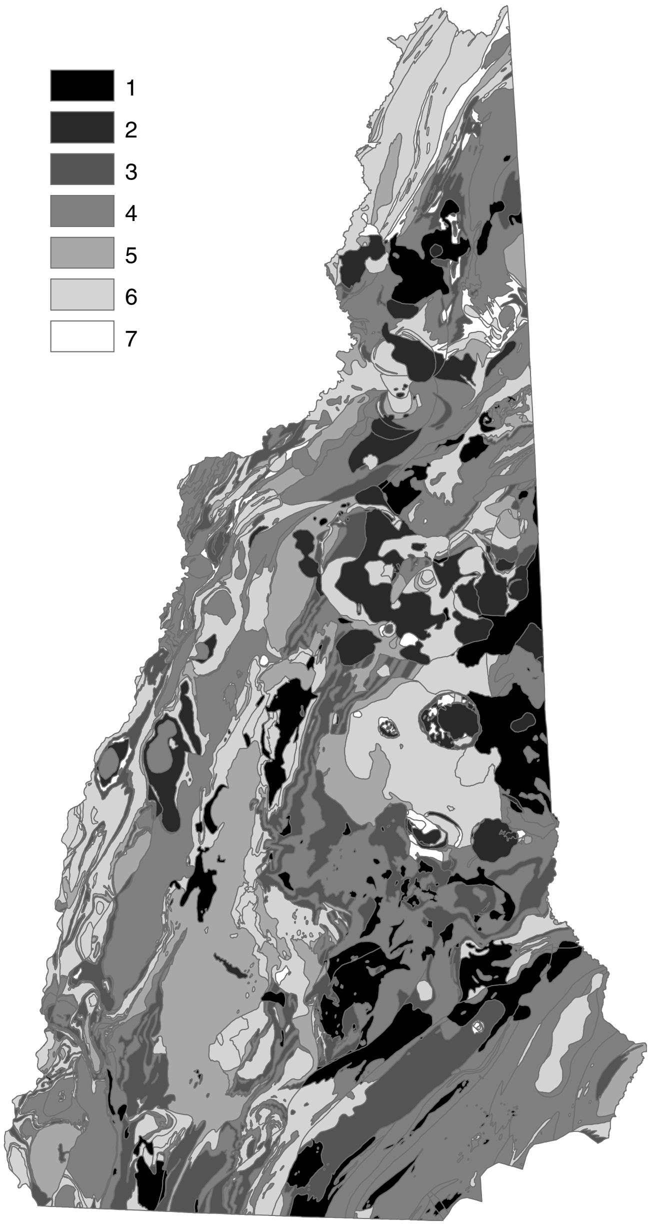

Fig. 1 Expert-assigned bedrock radon potential levels

A parameter setting is considered to be optimal if the output surface has a close-to-zero mean standardized error, a small root mean square error and a close-to-one root mean square standardized error (ArcGIS). Besides the "prediction map," which contains the interpolated values, the corresponding "standard prediction error map" was also created for evaluating the certainty of the predicted value at each location. By applying a threshold to the "standard prediction error map," a map of low-uncertainty areas was created. Only the interpolated values within the low-uncertainty areas were used in the following analyses.

By overlaying the bedrock type map on the interpolated continuous residential radon concentration surface, the mean residential radon concentration for each bedrock type can be calculated using the "zonal" function in Spatial Analyst® of ArcGIS. A potential problem is that if the low-uncertainty areas are highly fragmented, the spatial autocorrelation problem could reemerge; However, under the chosen threshold of certainty, the low-uncertainty areas were not fragmented.

The bedrock types were then ranked based on their mean residential radon concentrations. This rank was then compared with the rank based on the expert-assigned radon potential levels. The Spearman Rank Correlation Coefficient was calculated to quantify the correspondence between the two ranks. During this process a potential relationship between the area of bedrock type and the Spearman Coefficient value was noted. To verify this finding, the calculation of the Spearman Coefficient was performed repeatedly, each time dropping the bedrock type with the least area and using the remaining bedrock types for the calculation. The last run used only the 15 largest (in terms of occupied area) bedrock types. The Pearson correlation coefficient (R) was calculated between the average areas of the bedrock types used in the calculations and their corresponding Spearman Coefficient values.

Results

The values in the "standard prediction error map" vary between 0.8003 and 3.0556. A value of 0.9 was used as a threshold of certainty. That is, an interpolated value would be used in the following analysis only if its corresponding "standard prediction error" is smaller or equal to 0.9. Figure 2 is a map of the used values.

Among the 153 bedrock types in the USGS geology map, 143 overlap with the low-uncertainty areas shown in Fig. 2. When all 143 bedrock types were ranked based on the mean residential radon concentration values and were compared with the rank based on the expert-assigned radon potential levels, the Spearman Rank Correlation Coefficient was 0.08. As the smallest-area bedrock types were sequentially excluded from the calculation, the Spearman Coefficient shows an apparent inclining trend. When only the 15 largest bedrock types are used for the comparison, the Spearman Coefficient reached 0.6. These 15 bedrock types occupy 64% of the total area of the low-uncertainty area. The two maps in Fig. 3 facilitate a visual comparison between the two ranks of the 15 bedrock types. The patterns in the two maps show general similarity, but the differences are also apparent.

Figure 4 illustrates the process of sequentially reducing the number of bedrock types in the calculation through exclusion of the smallest-area bedrock types. In Fig. 4, the Spearman Coefficient values are plotted against four variables: the average area of the bedrock types, the smallest area of bedrock type, the number of bedrock types and the percentage of the low-uncertainty area occupied by the included bedrock types. Figure 4 shows that as bedrock types with the smallest area are sequentially excluded, the correlation coefficient generally increases. The R between the Spearman Coefficient and the average area of the used bedrock types is 0.81. Two obvious outliers occurred between average areas 600 and 700 km^2, corresponding to the bedrocks Jo1h and Oo2-3A. Jo1h has an area of 237 km^2 and the highest mean residential radon concentration value among all the 143 types, but its geologist-assigned radon potential level is 6, the second to the lowest one. Oo2-3A has an area of 200 km^2 and has a very low mean residential radon concentration value, but its radon potential level assigned by the geologist is 2. With these two outliers removed, the Spearman Coefficient values to the left of the two outliers in Fig. 4 significantly increased and the R between the Spearman Coefficient values and the average area of the included bedrock types increased to 0.85.

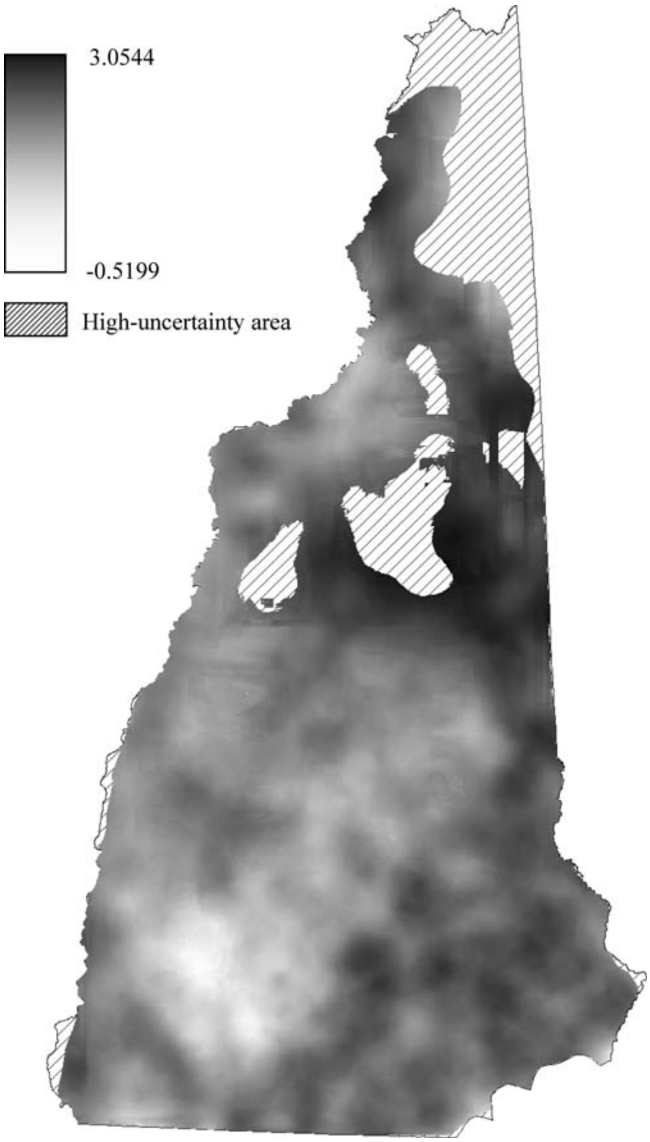

Fig. 2 Interpolated surface of residential radon concentration in New Hampshire (logarithmically transformed)

Discussion

Using a large database of residential radon concentration measurements and a detailed knowledge-based classification of bedrock radon potentials, this study examined the spatial association between residential radon concentration and bedrock type. Particularly, this research evaluated the usefulness of expert geological knowledge in predicting and mapping the risk of residential radon exposure. This evaluation was performed through a comparison between two ranks of the bedrock types, one based on the mean residential radon concentration within the spatial extent of each bedrock type, and the other based on the expert-assigned radon potential level. The mean residential radon concentration of a bedrock type was not calculated directly from the sample measurements, but was instead obtained from a continuous surface generated from the samples through kriging interpolation. Kriging allows for estimation of the uncertainty in the interpolated result. In this study, only the interpolated values with low uncertainties were used in the following statistical calculation and comparison. The correlation between the two ranks was quantified using the Spearman Rank Correlation Coefficient.

The Spearman Coefficient values indicate that the two ranks overall have a positive correspondence, although this correlation was relatively weak (0.08) when all the bedrock types are used. The Spearman Coefficient value increased as the bedrock types of small area were excluded from the calculation. The results demonstrate a strong positive correlation (R = 0.81) between the Spearman Coefficient value and the average area of the bedrock types used in the comparison.

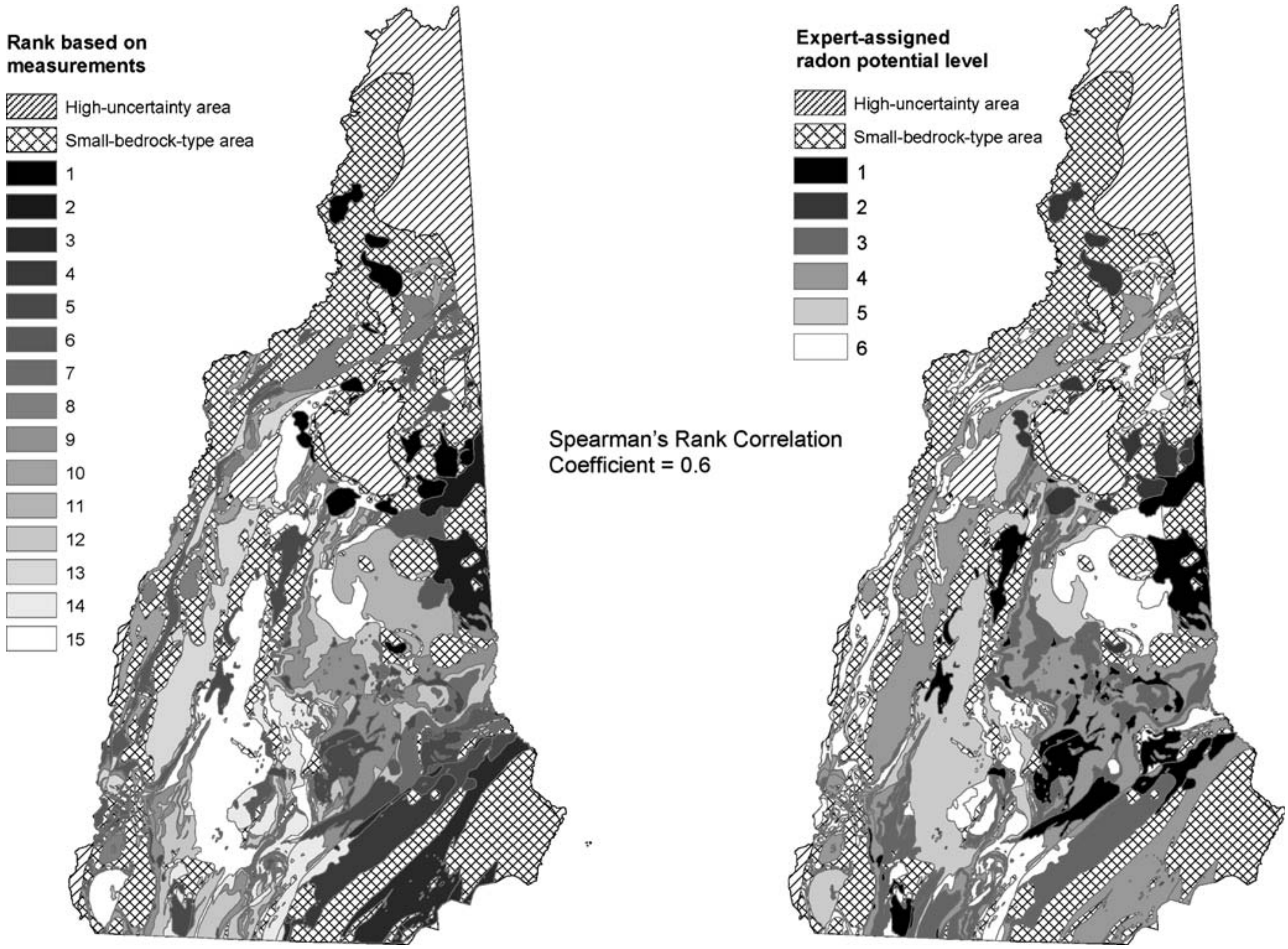

Fig. 3 Comparison on the 15 largest bedrock types in New Hampshire

This result has three possible and nonexclusive interpretations: (1) the expert knowledge may be more accurate on major bedrock types in an area; (2) the properties of large bedrock types may be more directly reflected in the residential radon concentration; and (3) the expert knowledge of the minor bedrock types may still be correct, but the interpolation overly smoothed the values for those bedrock types, due to their small areas and few samples. To gain a more in-depth understanding of this result, further research and more sampling are needed.

The interpolation used in this study was a global process that did not consider the possible limitations set by the bedrock type boundaries. As shown by Fig. 1, there are many bedrock type polygons with radon potentials quite distinct from their neighbors. Some other researchers used local interpolation to address this break-line issue. In their studies, the interpretation was restricted within each polygon (Kemski et al. 1996, 2001, 2005). At the beginning of this study, local kriging was indeed tested, but it turned out that the overall uncertainty from the local process was higher than that from the global process and the border areas of many polygons received unreasonable values from the local interpretation, which led to a decision that the result from the global process should be used. The unreasonable values seem to result from the reduction of information available to some border locations caused by the local process. For example, in a local process a sample on the *other* side of the border would not be used in the calculation for a location on *this* side of the border, even if the sample is very close to the location. The global process was considered acceptable, because while the autocorrelation model was derived using the entire sample set, the calculation for a specific location was only based on a few samples that are closest to the location, which limited, especially for large polygons, the possible bias caused by over smoothing. Nevertheless, over smoothing may still be significant for those small bedrock types, which is a possible reason for the mismatch between the expert's knowledge and the

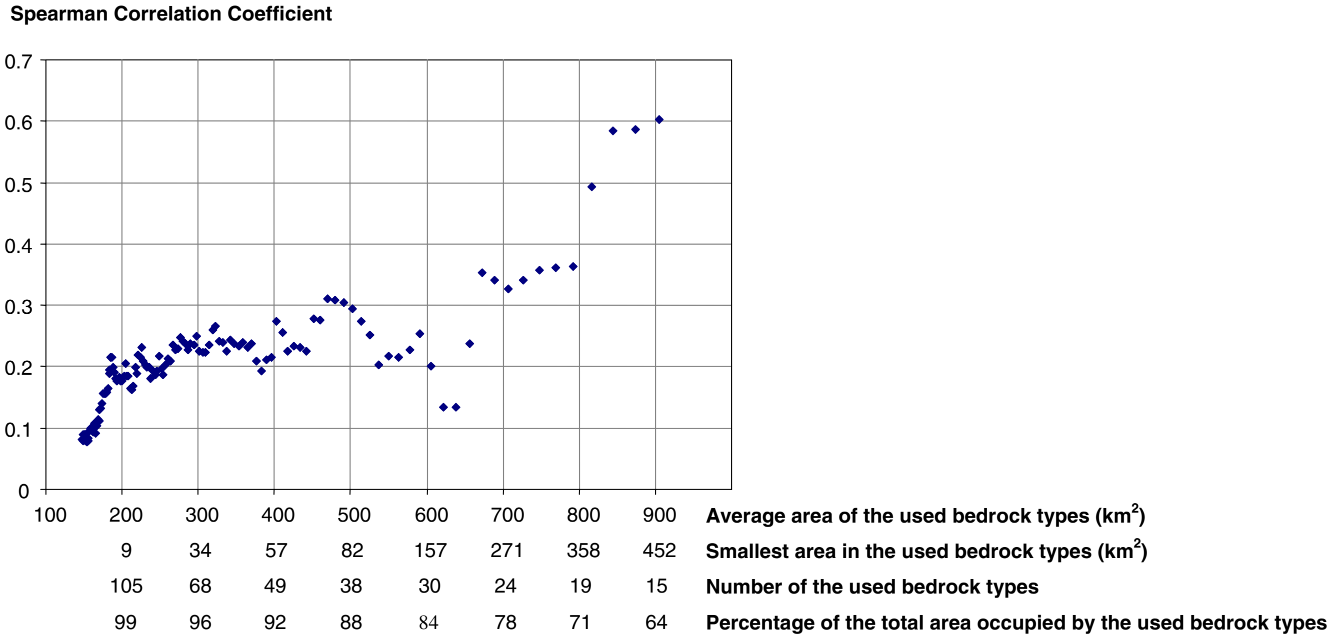

Fig. 4 Relationship between the Spearman Correlation Coefficient and the area of bedrock type

interpolated values on those bedrock types. A solution to this problem is to increase the sample sizes on those small bedrock types, which is a sampling strategy that should be considered by the radon measurement collection program of the state.

This case study suggests that the expert's geological knowledge can be useful in predicting and mapping the risk of residential radon exposure, but this usefulness may be limited, especially in areas overlaying bedrock types with very small areas. Residential radon concentration is a function of multiple factors and their complex interactions. In areas overlaying bedrock types with small areas, other factors such as soils, groundwater, construction characteristics, may exert more influence on the residential radon concentration than the bedrock does. A map of radon exposure risk created based on bedrock types therefore should be interpreted with caution. As Gundersen and Schumann (1993) emphasized, this kind of map should never be considered as a substitution of an actual indoor radon test.

In this study, knowledge from only one geologist was used, and the radon potential classification of specific bedrock types may involve some ad hoc factors. However, the clear pattern in the relationship between the Spearman Correlation Coefficient values and the bedrock type area suggests that the classification is not random and the findings from this study may be useful in other areas in the USA.

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