EXAMINATION OF OHIO INDOOR RADON DATA

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Abstract

It is estimated that 700 to 1300 people die annually in Ohio from radon-induced lung cancer. The Ohio Radon Information System (ORIS) available online at http://www.radon.utoledo.edu has been developed to create the much-needed awareness among Ohio's citizens on radon concentrations in their localities and the problems associated with radon exposure. Over the years, the database (made available by testing laboratories, Ohio Department of Health (ODH), Ohio Environmental Protection Agency (EPA), and universities) has been expanded to 159,340 radon observations from homes; 1,341 radon observations from schools; 1,283 radon observations from drinking water; 28,062 radon observations from licensed mitigation contractors; and 77,581 radon observations from licensed testers and specialists. This paper presents various statistics of the analyses performed on the radon databases developed in the last 22 years.

For various reasons, radon concentration data are not available for each and every zip code, in Ohio. In places where data are unavailable, radon data may be estimated by applying effective interpolation techniques allowing for comprehensive radon mitigation planning. This paper presents two interpolation techniques for estimating radon concentration values in missing zip codes. Initial results concerning the relative performance of such techniques are shown, and the impact of the interpolated data on radon awareness in Ohio is discussed.

Introduction

Radon is a colorless, naturally-occurring, radioactive, inert gas formed by the natural breakdown of uranium in soil, water and rock. Radon gas drifts upward through the ground to the surface of the soil and seeps into the buildings through foundation cracks. Radon gas is formed naturally by radioactive decay of uranium present in geologic materials. The major sources of radon gas in Ohio are 'Ohio shale' and soil. Elevated radon levels have been discovered in every state. The United States Environmental Protection Agency (U.S. EPA) estimates that as many as eight million homes throughout the country have elevated levels of radon (EPA Report, 2004). If the indoor radon concentrations exceed the EPA recommended action level of 4 pCi/l, immediate measures should be taken to reduce the radon level to 2 pCi/l (Kumar, 2001). Radon exposure is responsible for about 21,000 lung cancer deaths per year in the United States (EPA Report, 2003).

Ohio Department of Health (ODH) initiated an indoor radon gas program in the late 1980's to reduce the number of deaths attributable to radon. In the 1990s, ODH started encouraging the reduction of radon concentrations in houses and schools to a safe level through a number of mitigation methods. In 2001, Ohio passed a law that required radon mitigation contractors to report mitigation data on homes to the ODH (ODH Chapter, 2001). As a result of the new law, two new databases were developed to study radon mitigation systems and to track observations by testers.

The University of Toledo (UT), under several research grants from the ODH and the Ohio Air Quality Development Authority (OAQDA), developed the Ohio Radon Information Systems (ORIS), and a website (Harrell, 1993; Harrell, 1991; Kumar, 2001; Kumar, 1990; and Ojha, 2001). As of June 2010, the radon database developed and maintained by UT has 159,340 radon observations from homes; 1,341 radon observations from schools; and 1,283 radon observations from drinking water. In addition, as of June 2009, the mitigation database has been expanded to 28,062 radon observations and the tester database has been expanded to 77,581 radon observations. The purpose of developing and maintaining the ORIS database is to analyze radon data across the state of Ohio and produce results that help create public awareness and understanding of the hazards of radon gas and, therefore, reduce any of its concentration levels in places that surpass the EPA's action limits.

This paper summarizes the key results obtained from analysis of ORIS data and compares the performance of two different interpolation techniques that help predict radon concentrations in unmeasured zip codes. The two interpolation techniques used in this study are kriging and cokriging.

Methodology

The ORIS consists of five different databases or modules: home database, school database, water database, mitigation database, and tester database.

Home Database

The home database provides information on the radon gas concentrations measured using radon detectors in Ohio homes. The home database was initially handled using the ORACLE/MS Access database (Joshi, 2002). However, due to the yearly increase in the number of radon records in the homes database it is currently handled by SQL Server 7.0/MS Access and Microsoft Excel 2007. Data for homes is provided by various organizations and radon testing laboratories as electronic files. The raw data is processed before inclusion in the database. As of June 2010, there are 159,340 radon data points in the homes database. Queries were built in MS Access to analyze the radon statistics based on counties and zip codes. The statistics computed include maximum (Max.), minimum (Min.), arithmetic mean (AM), geometric mean (GM), standard deviation (SD), coefficient of variance (CV), median (Md), quartile 1 (Q1), and quartile 3 (Q3). Using Geographical Information Systems (GIS) software, zip code and county maps are drawn to visually represent the radon concentrations in Ohio. These statistics and color-coded GM maps, for the state of Ohio based on counties and zip codes, are available online on the ORIS website. Queries were also built to identify zip codes and counties with radon GM concentrations > 4 pCi/l and 8 pCi/l. In this study, the unmeasured zip codes or zip codes where the data were not available were estimated using two different interpolation techniques that include kriging and cokriging. Some studies have provided discussion on estimating radon concentrations for missing zip codes (Kumar, 2007; Manthena, 2009; and Akkala, 2010).

School Database

The School database is very small compared to the home database. MS Access is used to handle the school database. The radon measurements in schools in Ohio are provided by the ODH. Queries such as schools tested by county; number of schools tested each year; schools with radon GM concentrations > 4 pCi/l, > 8 pCi/l, > 20 pCi/l; percentage of rooms having radon concentrations > 4 pCi/l in each school; and schools with more than 15 rooms and radon concentrations > 4 pCi/l are used to analyze the data. The school statistics query provides the number of schools tested in each county, AM, GM, SD, and variance of radon concentrations for 1,341 schools in the 63 counties where data were measured as of June 2010. The visual representation of the county map with the percentage of school rooms with radon GM concentrations > 4 pCi/l is drawn using GIS and is available online on the ORIS website.

Water Database

The water database contains data collected from both public water wells and private water wells. The public water wells database was provided by the Ohio EPA while radon data for the private water wells were obtained from various Ohio universities' MS theses and research programs. Queries were built in MS Access which show the zip code, county, radon concentrations, and date of testing for both the public and private water wells. As of June 2010, of the 1,283 water supply systems in the water database; 216 are public water wells, and the remaining 1,067 are private water wells. It is difficult to obtain new data in this area.

Mitigation Database

Licensed mitigation contractors perform tests and submit the results to the ODH. This data is manually entered in to an Excel spreadsheet. The data contains information of 1) license number of the contractor; 2) name of the contact; 3) phone number of the contact; 4) address of the contact; 5) county, zip code, city and state; 6) system type; 7) start and completion dates; 8) pre-mitigation and post-mitigation levels; 9) quarter of the year; and 10) year in which measurements were made. The missing data values are assigned as "NA" for alpha numeric type and "-1" for numeric values.

The mitigation data (Kumar, 2003) is imported to MS Access to analyze, store, and update the mitigation data. Currently (June 2009), the mitigation database consists of 28,062 radon observations. Queries were designed in MS Access for analyzing mitigation data. These queries determine the total number of tests performed by each licensed contractor, average removal efficiency by each type of system, counties with pre-mitigation radon level > 4 pCi/l, pre-mitigation radon level between 4 pCi/l and 20 pCi/l, and pre-mitigation level greater than 20 pCi/l.

Tester Database

The radon tests conducted by licensed testers are submitted to the ODH and these records are then passed to the UT Civil Engineering Department. As of June 2009, the tester database has been expanded to 77,581 radon observations. The tester database includes information on 1) license number of the tester; 2) name of the contact; 3) street address of the contact; 4) zip code, city, county, and state; 5) device code; 6) test type; 7) start and finish dates of the test; 8) radon concentration level; 9) quarter of the year; and 10) and year in which the measurements were made.

Database maintenance procedures adopted for the tester database are similar to the maintenance procedures adopted for the mitigation database. Tester results are entered manually into an Excel spreadsheet, processed, and checked for accuracy to avoid transcription errors. The data is then imported to MS Access to run queries. Queries are run to determine the number of records tested by each licensed tester, counties with radon level > 4 pCi/l, radon statistics that include the number of radon measurements, Max., Min., AM, GM, SD, and variance based on county and zip codes. The queries are built in such a way that they do not consider missing data during the analysis.

Interpolation Techniques

Radon data is not available in each and every zip code due to inapproachability, cost effectiveness, and time constraints. Two interpolation techniques: kriging and cokriging are investigated in this study to estimate the radon concentrations for unmeasured zip codes. These interpolation techniques use the available radon data in known locations to estimate the radon data for unmeasured zip codes which will help to render an effective plan to mitigate the radon concentrations in Ohio. An overview of the two interpolation techniques is given:

Kriging: Kriging is a geostatistical technique, generally used to interpolate the value of a random field (e.g., the elevation, z, of the landscape as a function of the geographic location) at an unobserved location from values at observed locations. This method not only produces prediction surface, but also provides an error and uncertainty surfaces. Kriging is mainly divided into two different functions: predicting and quantifying the spatial structure of the data. This interpolation technique is very flexible and allows the user to investigate graphs of spatial autocorrelation. This technique uses statistical models that allow a variety of map outputs including predictions, prediction standard error, standard error of indicators, and probability.

Cokriging: Cokriging interpolation technique is similar to kriging that perfoms better estimates using a secondary variate, sampled more intensely than the primary variate. If the primary variate is difficult or expensive to measure, cokriging uses secondary variate to predict the data without having to more intensely sampling the primary data. This method uses radon as the primary variate and uranium as the secondary variate. Ordinary cokriging technique has been found to give the most reproducible estimations (Ahmed, 1987).

More information about these two interpolation techniques can be found in the open literature. Our current research is on the use of Artificial Neural Networks to predict radon concentrations in unmeasured zip codes (Akkala, 2010 and Akkala, 2011).

Results and Discussion

The analysis of radon data from the five databases help in better understanding the radon problem in Ohio. The analysis of radon data and results obtained from running the queries provide information to the concerned authorities to take necessary steps in evaluating various steps to mitigate radon concentrations to acceptable levels (EPA action limit of 4 pCi/l).

Home Database

The analysis of home database showed that out of 88 counties in Ohio, 29 have radon GM levels more than 4 pCi/l, with Licking being the only county with radon GM level greater than 8 pCi/l. Of the 1544 zip codes homes data, 32.64% zip codes have radon GM levels greater than 4 pCi/l and 8.04% zip codes have radon GM levels greater than 8 pCi/l. Based on the 159,340 radon homes database, the GM of radon concentrations in the state of Ohio is 3.99 pCi/l. Maximum radon concentration of 927.6 pCi/l is accounted for the zip code 43952 in "Jefferson" county. Figure 1 provides the visual representation of radon GM concentrations in Ohio on a county and zip code basis respectively, thereby giving a better idea on the radon distribution in Ohio.

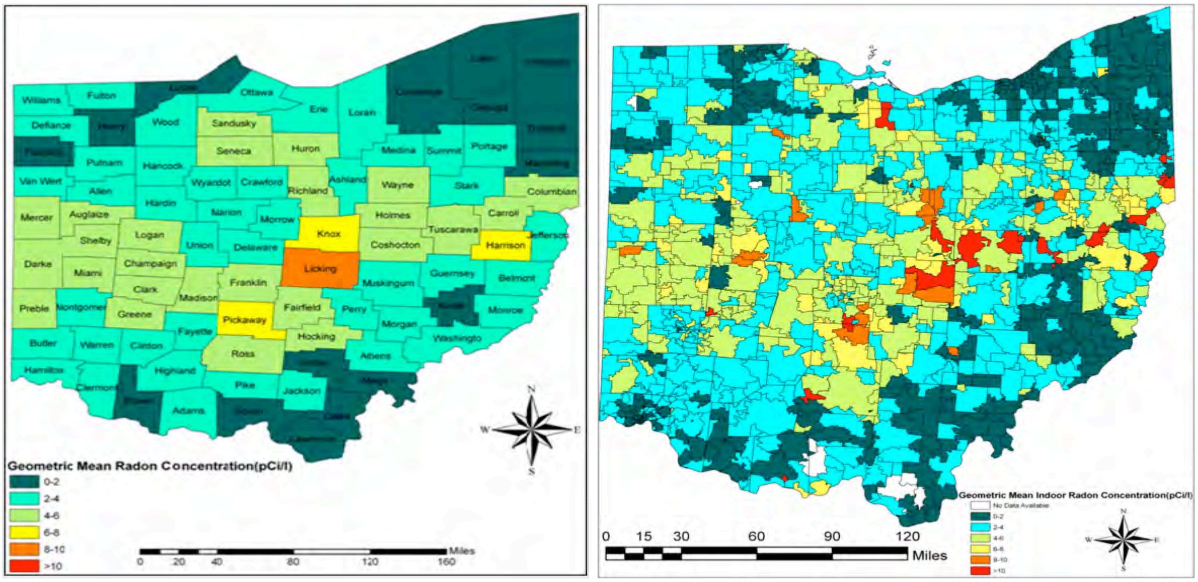


Figure 1: Geometric Mean of Radon Concentration in Ohio Counties and Zip Codes

School Database

Sixty three (63) counties and 1,341 schools have been tested under the ODH School Testing Program as of June 2010. Analysis of the radon data in schools on a county basis revealed a school in Belmont County having a maximum radon concentration greater than 85.5 pCi/l. The school also had 11 out of 39 school rooms tested with radon concentration greater than 4 pCi/l. Figure 2 provides the visual representation of counties in Ohio with percentage of school rooms over 4 pCi/l. It can be observed from Figure 2 that Pike County schools have approximately 50-60% of schools with radon concentrations over 4 pCi/l. Overall 28% of the schools in Ohio have a potential for at least one room in excess of the EPA action level of 4 pCi/l.

Water Database

Table 1 provides a summary of the results associated with radon concentrations in private wells. Of the 1,067 private water wells, 65 wells have radon concentration greater than or equal to 1000 pCi/l. Of these 65 wells, 28 are located in Logan County and 13 in Delaware County (Table 1). Seven private wells showed radon concentration over 3000 pCi/l. However, none of the public water supply systems have radon levels more than 1500 pCi/l. Only two public wells showed radon concentration greater than 1000 pCi/l.

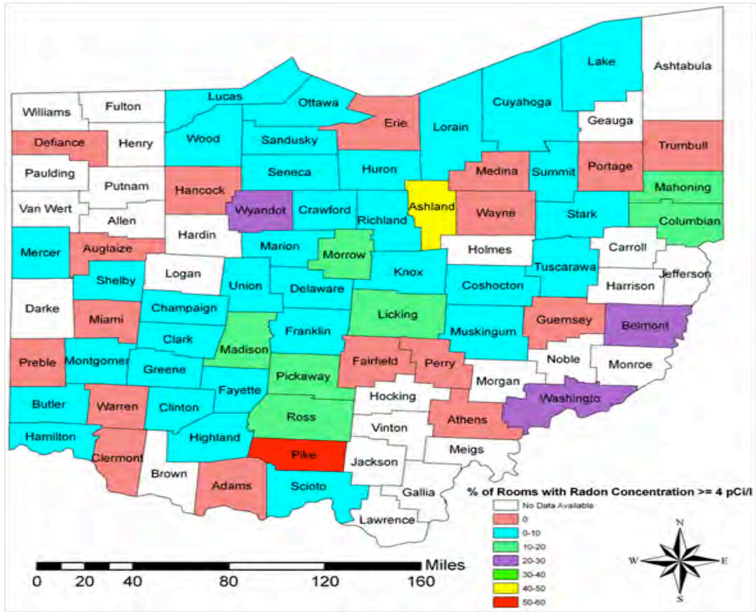


Figure 2: Counties with % of School Rooms with Radon Concentration >= 4 pCi/l

Mitigation Database

Mitigation testing program results provide an insight into the effectiveness of the program in Ohio. As of June 2009, of the 28,062 radon mitigation observations; 21,607 (76.99%) records are complete with both post-mitigation and pre-mitigation levels. Over the years, there has been an increase in the percentage of complete records submitted. Currently, the percentage of complete records is 94%, vs. 20.38% in 2001. This shows that the efforts of the ODH are productive which increased data quality.

Table 2 presents the average removal efficiency by each type of system for the year 2008. The analysis of the mitigation systems revealed that the Sub Slab Depressurization (SSD) system performs well in mitigating the radon concentrations to below 4 pCi/l (refer Table 2). Figure 3 shows the variation of removal efficiency with pre-mitigation and post-mitigation levels for the best mitigation system for the year 2008. It can be observed that efficiency of the system decreases with a decrease in the pre-mitigation level, because it is difficult to reduce the radon concentrations below a certain level. Figure 3 also shows that the removal efficiency decreases with an increase in the post-mitigation level.

Tester Database

The query results obtained from the tester database provide an insight into the radon concentration levels in different counties and zip codes across Ohio. Of the 77,581 records reported as of June 2009; 77,123 records (99.41%) are complete. Table 3 provides the statistics for counties with GM radon levels >= 4 pCi/l. There are 29 counties that have radon test levels above 4 pCi/l. Harrison (GM = 10.25 pCi/l) and Perry (GM = 8.65 pCi/l) are the two counties having GM radon levels > 8 pCi/l.

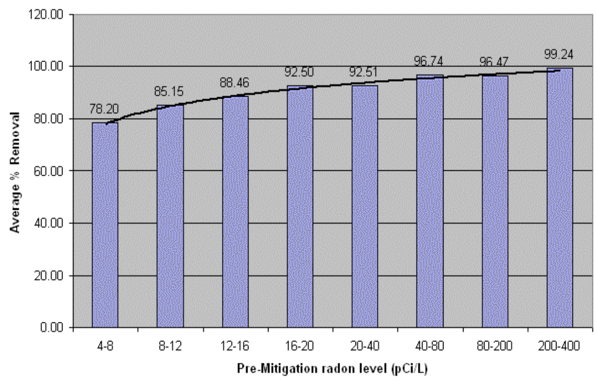
Table 1: Radon Concentration in Private Water Wells in Ohio Counties

Counties	Total No. of Wells	Max. Radon Conc. (pCi/l)	Min. Radon Conc. (pCi/l)	Avg. Radon Conc. (pCi/l)	No. of Wells with Radon Conc. ≥ 1000 pCi/l
Butler	7	571	217	415.00	0
Champaign	80	1491	73	355.85	2
Clark	8	1386	172	436.88	1
Clermont	1	163	326	163.00	0
Crawford	78	1021	13	143.42	1
Darke	1	231	231	231.00	0
Delaware	**60**	**2314**	**2**	**599.12**	**13**
Erie	181	3104	20	285.82	6
Fulton	3	172	119	147.00	0
Greene	4	703	200	438.75	0
Hamilton	2	380	213	296.50	0
Hancock	7	470	180	322.86	0
Hardin	49	996	44	238.73	0
Henry	1	510	510	510.00	0
Huron	149	2010	5	230.82	7
Logan	**212**	**7511**	**25**	**553.99**	**28**
Marion	74	1574	26	257.61	3
Miami	4	413	174	248.00	0
Montgomery	6	637	249	406.67	0
Morrow	93	3425	25	303.15	4
Ottawa	2	150	130	140.00	0
Paulding	1	190	190	190.00	0
Preble	3	782	184	507.67	0
Sandusky	3	130	80	96.67	0
Seneca	9	220	80	129.89	0
Union	5	334	82	210.40	0
Warren	4	542	340	442.00	0
Williams	8	245	148	185.25	0
Wood	6	560	200	320.00	0
Wyandot	6	180	96	132.00	0

Table 2: Average Removal Efficiency by Each Type of System for Year 2008

Type of System	Number of Records	Average % Removal	Standard Deviation
SSD	2706	82.50	13.25
SUMP/DTD	604	85.40	9.50
SSD/SMD	574	86.25	9.75
DTD	162	86.00	14.25
SUMP/DTD/SMD	41	85.25	10.50
SUMP/SSD	38	77.00	18.00

SUMP VENTILATON	33	88.33	4.67
SSD/DTD	23	83.50	12.67



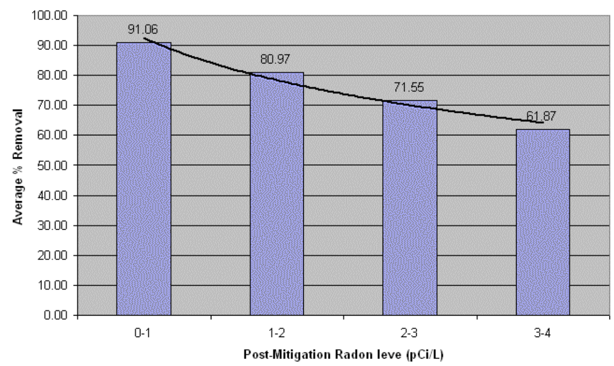


Figure 3: Variation of Removal Efficiency with Pre-Mitigation and Post-Mitigation Levels for the Best Performing System for Year 2008

Table 3: Statistics for Counties with Tester Radon Concentration >= 4 pCi/l

County	No. of Records	Max.	Min.	AM	GM	SD	Variance
Harrison	12	50.50	0.80	10.74	10.25	6.61	83.93
Perry	9	36.60	1.70	10.70	8.65	12.22	62.29
Ross	16	44.60	0.50	8.15	7.91	2.65	70.83
Logan	30	46.10	0.40	9.13	7.56	7.49	86.55
Mason	2	10.10	5.20	7.65	7.25	3.46	45.29
Van Wert	4	16.70	0.80	6.82	6.77	1.20	40.75
Erie	131	273.20	0.05	13.34	6.76	16.28	104.27
Carroll	34	62.10	0.40	7.87	5.69	8.78	84.24
Madison	37	36.60	0.50	7.46	5.59	7.44	94.59
Pickaway	35	22.60	0.40	6.31	5.48	3.95	69.38
Darke	17	30.10	0.60	7.07	5.32	7.44	101.99
Marion	72	53.60	0.20	8.30	5.32	7.83	89.95
Auglaize	13	13.10	0.50	5.52	5.08	2.48	54.11
Coshocton	8	7.80	0.70	5.30	5.08	2.40	77.56
Pike	164	16.50	0.50	5.79	4.99	3.10	53.51
Licking	585	296.60	0.20	9.75	4.98	13.80	135.96
Knox	138	258.00	0.40	14.60	4.95	26.13	158.11
Columbiana	116	77.10	0.20	8.83	4.93	10.09	105.32
Champaign	24	36.80	1.00	5.72	4.90	6.07	59.69
Highland	6	8.80	2.30	4.88	4.88		
Fairfield	274	54.00	0.20	7.58	4.86	7.41	97.47
Preble	21	21.70	0.10	5.37	4.61	4.47	69.15
Guernsey	4	6.70	1.30	4.50	4.50		

Morrow	29	22.50	0.30	5.24	4.25	3.76	69.50
Stark	1920	111.00	0.10	6.84	4.21	9.03	128.76
Tuscarawas	526	134.00	0.05	7.28	4.02	10.01	127.25
Delaware	1797	735.00	0.10	6.62	3.99	9.96	132.88
Franklin	7891	939.00	0.05	6.88	3.98	10.07	144.01

Comparative Performance of Interpolation Techniques

The radon data set available at The University of Toledo, collected from various radon testing organizations, consists of radon data for 1075 zip codes until 2010, whereas there are 1862 zip codes mentioned in the GIS data file of Ohio. Using kriging and cokriging interpolation techniques, radon concentrations for unmeasured zip codes are predicted and different statistical performance measures are computed to determine the relative performance of the two techniques. Figure 4 presents the spatial distribution of radon concentration maps obtained on using kriging and cokriging interpolation techniques. Both these maps exhibit similar pattern of radon concentration distributions across the state of Ohio. Relatively high concentrations are observed in the central and western parts of Ohio as can be seen from Figure 4. It was also observed that these maps exhibit similar pattern to the uranium distribution in Ohio. The uranium map can be found online on the ORIS website.

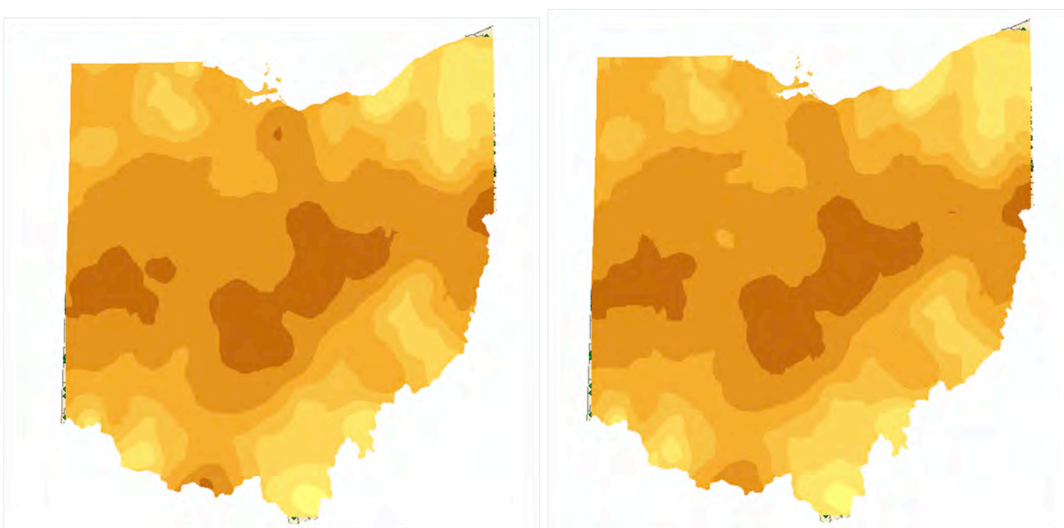


Figure 4: Spatial Distribution of Radon Concentrations in Ohio using Kriging and Cokriging Interpolation Techniques (Respectively)

Table 4 presents the summary of different statistical performance measures used to compare kriging and cokriging interpolation techniques. The performance measures used to compare the two techniques are model bias (MB), normalized mean square error (NMSE), correlation coefficient (Corr.), factor of two (Fa2), fractional bias (FB), and fractional standard deviation (FS) (Hanna, 1991). An interpolation technique is considered to be ideal and perfect if the FB and NMSE are equal to zero. However, no technique is perfect in making accurate predictions. Kriging and cokriging interpolation techniques are deemed acceptable if the performance measures meet the criteria of having (i) NMSE $\leq$ 0.5, (ii) -0.5 $\leq$ FB $\leq$ 0.5, and (iii) Fa2 $\geq$ 0.80. It can be seen from Table 4 that both kriging and cokriging techniques meet all the three requirements of NMSE, FB, and Fa2. One can observe both the techniques to over predict (negative bias) radon concentrations. Also, the predicted results using both these techniques have shown close correlation with the observed data as can be seen from correlation coefficient values in Table 4. One can also observe cokriging interpolation technique is slightly better than kriging interpolation technique, because the performance measures for cokriging technique are found to be relatively closer to the ideal values of FB, NMSE, and Fa2.

Table 4: Performance Measures for Interpolation Techniques

Performance Measures	Mean	Sigma	MB	NMSE	Corr.	Fa2	FB	FS
Observed	3.42	2.74	0.00	0.00	1.00	1.00	0.00	0.00
Kriging	3.53	2.47	-1.25	0.47	0.876	0.99	-0.358	0.101
Cokriging	3.49	2.34	-1.23	0.45	0.883	0.99	-0.353	0.114

Percentage Change in Zip Codes Exceeding 4 pCi/l Based on Kriging and Cokriging Interpolation Techniques

Kriging and cokriging interpolation techniques were used to predict radon concentrations in unmeasured zip codes and these results showed that there are significant number of zip codes that exceeded 4 pCi/l. The analysis of available zip code radon data and the interpolated radon data for missing zip codes using kriging technique showed that 32.60% of zip codes have concentrations above 4 pCi/l as compared to 28.68% of zip codes based on measured radon data, while cokriging technique showed 31.90% of the zip codes to exceed EPA action limit of 4 pCi/l. These results indicate that more mitigation work is ahead for radon planners in Ohio.

Conclusion

An integrated Ohio radon information system has been successfully compiled from the data provided by government agencies, university researchers, and commercial testing companies. The information available from the database is useful in assessing the extent of the radon problems in Ohio's homes, public water systems, and schools. It was also possible to determine the best mitigation system to control radon gas problem in Ohio homes and identify the counties and zip codes with radon test levels greater than EPA action limit of 4 pCi/l. The radon website developed during the project helps in creating awareness among Ohio's citizens on radon issue and provides information on steps to reduce radon exposure. After predicting the radon concentrations for unmeasured zip codes using the two interpolation techniques, it was observed that cokriging technique showed relatively better performance than kriging technique. Interpolated data shows that more mitigation work is ahead for many zip codes that were not known before.

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