

**A GIS Multi-Criteria Analysis of Indoor Radon Risk in Columbia County,
Pennsylvania**

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Dr. Chris Shaffer

4/20/23

Date



Dr. Eric Pallant

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Indoor radon is a colorless and odorless radioactive gas that poses a potential threat to all homeowners. When uranium decays in the rocks and soils underlying a house, it forms radon. Radon can escape from the ground and find its way into a home through cracks in the foundation or basement walls. As a result of its radioactive properties, radon is the leading cause of lung cancer in non-smokers. Columbia County, Pennsylvania faces some of the highest radon levels in the state but still has relatively few radon tests performed. A GIS multi-criteria analysis was conducted to better understand the risk that Columbia County faces and encourage proactive testing behaviors. The analysis used an analytical hierarchy process and weighted linear combination approach to first assign weights to radon risk factors including lithology, soil permeability, proximity to faults, water supply, and home age, and then combine them. This produced a radon risk index for the county that identified specific areas that may benefit from additional radon education and outreach. The risk index indicated that almost 50% of the county's area is classified as high risk. The results of this analysis were made accessible to the public via ArcGIS Story Maps (<https://arcg.is/efmuX>) to help inform Columbia County residents about their home's radon risk. This approach can be replicated for other geographical areas, as any community can benefit from increased radon awareness.

Introduction

Radon Properties and Formation

Radon gas is a highly dangerous, radioactive substance that every homeowner should be aware of (Pennsylvania Department of Environmental Protection [PA DEP], n.d.). Small amounts of radon occur naturally in Earth's atmosphere, though generally, it is not considered a threat when present outdoors. However, radon becomes a serious human health concern when it becomes trapped in a structure such as a home, office building, or mine (United States Environmental Protection Agency [U.S. EPA], 2022). When that occurs, the gas is referred to as indoor radon. Radon gas is odorless and colorless, meaning that the only way to detect its presence in an enclosed space is through testing (U.S. EPA, 2022; Centers for Disease Control and Prevention, 2021).

Uranium, a radioactive element commonly found in rocks and soils, is the primary source of radon. Radon forms when uranium undergoes radioactive decay, a natural and spontaneous process in which an atom loses energy in the form of radiation (Figure 1) (Otton, 1992; U.S. EPA, 2023). The atoms that undergo radioactive decay are known as radionuclides. When decay occurs, the radionuclide is transformed into a new element, and will continue to repeat this process until it reaches a stable state (U.S. EPA, 2023). Uranium, like every radionuclide, has a specific decay chain, or a series of elements that it will transform into (Figure 1). As the decay chain of uranium progresses, it eventually becomes the element radium, which, like uranium, is solid at room temperature. When radium decays, each atom ejects an alpha particle, creating a radon atom in the gaseous phase. The newly formed radon atom recoils in response to the ejection of the alpha particle. The position where this recoil motion occurs within a rock or soil affects if the radon atom will be contained or escape from its source. If the radon is shot towards the pore spaces in the material, it is then able to exit the rock or soil and enter the air (Otton, 1992).

Radon in Homes

Indoor radon becomes an issue when radon gas is able to escape from the subsurface and find its way into a structure. There are a number of ways that this can occur. Radon can travel through networks of pore spaces in the rocks and soils it is found in. The more permeable those materials are, the easier it is for radon to find a route to the surface. Any additional pathways,

such as faults and fractures in the rock units, make it increasingly easy for radon to leave the subsurface (Churchill, 1991). Radon can also travel to structures through groundwater. Radon gas is able to dissolve in water and can accumulate in groundwater sources such as wells. When the contaminated water is expelled from a faucet, it releases the gas into the air (U.S. EPA, 2014).

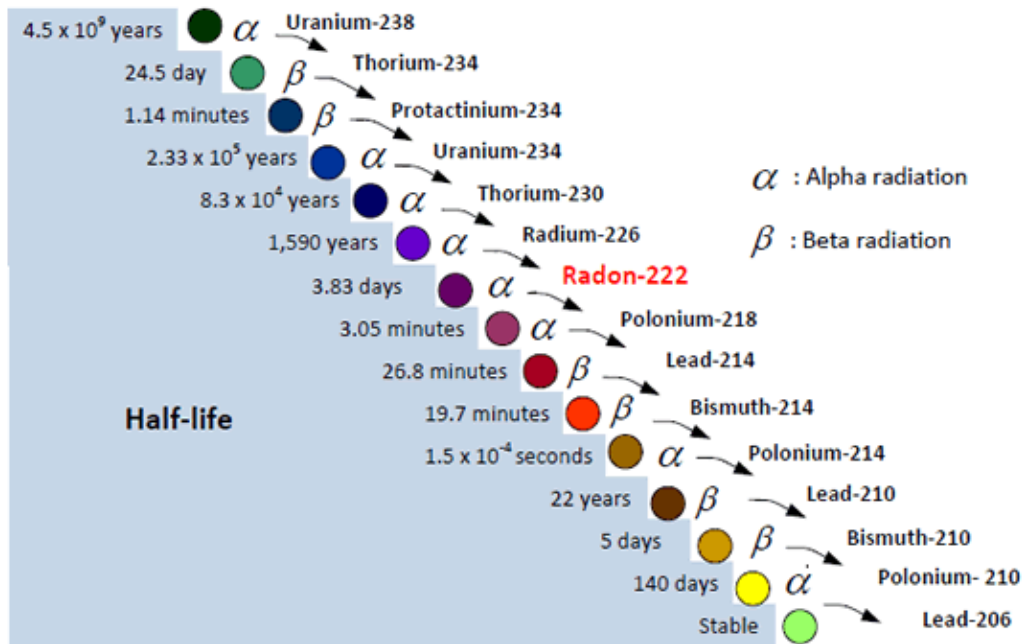


Figure 1. The decay chain for uranium. Retrieved from the Canadian Nuclear Safety Commission, 2014.

The main entry points for radon into homes are cracks in the walls and floors of basements and fractures in the foundation (Figure 2) (Lewis et al., 2019). These provide pathways for radon that has moved to the surface of the underlying rock and soil to make its way into the home. Basements tend to have higher radon levels because of their close proximity to the ground and because they provide many access points for radon gas to enter. However, radon can still be found in any part of the house or in homes without basements (PA DEP, n.d.). As buildings become increasingly airtight to improve energy efficiency, the risk of radon entering a home and remaining there increases because the contaminated air is prevented from leaving the house (Stanley et al., 2019).

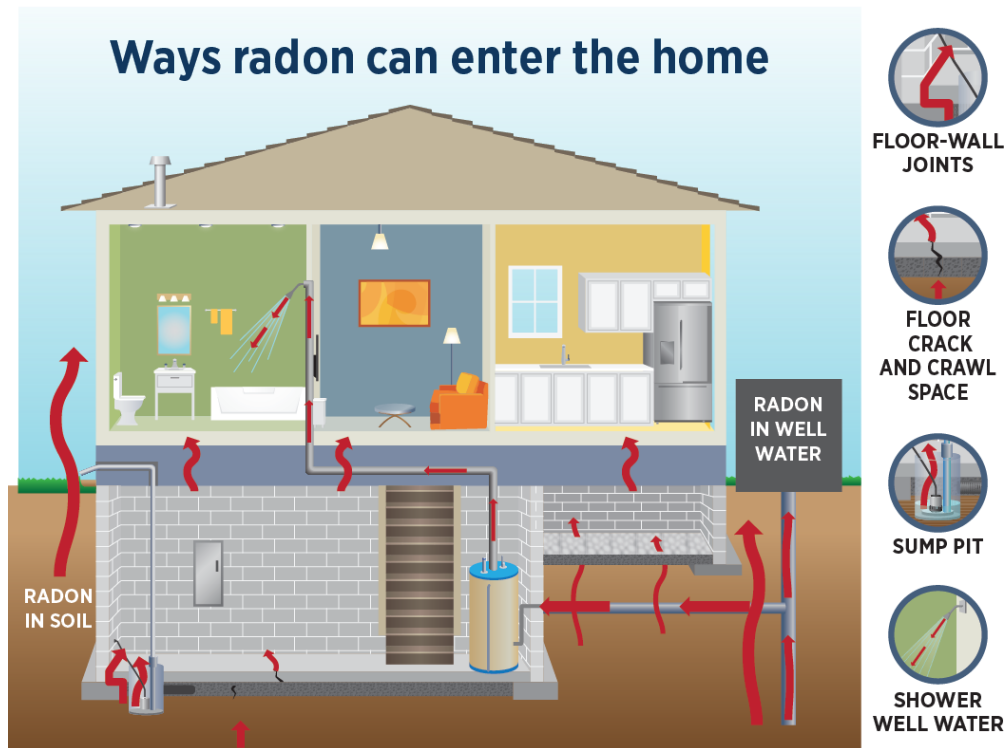


Figure 2. Examples of the most common ways radon enters a home. Retrieved from Massachusetts Environmental Public Health Tracking, 2022.

Health Concerns

Extended exposure to radon is the second leading cause of lung cancer worldwide, outranked only by smoking (World Health Organization, 2009). Radon causes cancer because of its radioactive properties. When the gas is inhaled, radon remains in the lungs and continues to decay. Every radionuclide has a specific half-life, which is the amount of time it takes for half of the radioactive atoms to decay (U.S. EPA, 2023). The half life of radon is 3.8 days, which is relatively quick compared to many other radionuclides. Just like uranium and radium, when radon decays it emits radiation and forms even more radioactive particles, this time in the form of polonium, followed by lead and bismuth (Figure 1) (Otton, 1992). These particles damage the cells of the lungs, and with long-term exposure, cause lung cancer (National Cancer Institute, 2011).

The connection between indoor radon and lung cancer is well established and has been documented by a number of studies (Barros-Dios et al., 2012; Field et al., 2000; Krewski et al., 2005; Wichmann et al., 2005). Recent calculations suggest that around 14-17% of lung cancer

deaths and 3% of all cancer deaths are caused by indoor radon. Further, it is estimated that 20,925 deaths in the United States alone occur each year because of radon (Gaskin et al., 2018). Given the known risk to human health, the U.S. EPA defines the action level for radon as 4 picocuries per liter (pCi/L), suggesting that levels of indoor radon greater than or equal to that amount pose a significant threat and should be remediated immediately. Despite defining an action level, the U.S. EPA also states that there is no known safe amount of radon and recommends that action should also be taken to remediate indoor radon when present in concentrations between 2 and 4 pCi/L (U.S. EPA, 2022).

Risk Factors Specific to Columbia County, Pennsylvania

Impoverished communities may be at a particularly high risk of indoor radon given disproportionate awareness and financial barriers that prevent access to testing and mitigation. Radon awareness significantly decreases with lower income levels. This was demonstrated in a study performed by the Colorado Department of Health and Environment that found only 37% of people with an annual income of less than \$15,000 knew about indoor radon, while that number rose to 85% for people with incomes above \$50,000 (Evans, 2016). Another study of over 2,000 people found that 28.5% of participants who interpreted their home's radon level as high or unsafe desired to fix the problem, but were not able to do so because of financial barriers (Irvine et al., 2022). These studies suggest that individuals living in poverty are more likely to be unaware of radon exposure, and if they are aware, have more difficulty remediating the issue.

According to the PA DEP, Pennsylvania has one of the most severe radon problems as compared to other states. They also report that approximately 40% of homes within the state have radon levels above the EPA action level (PA DEP, n.d.). The high risk that Pennsylvania faces may be partially attributed to the high levels of shale gas production in the state. During the extraction of shale gas, large amounts of radon are released. This radon can then contaminate the groundwater around the drilling site or be carried directly to homes with the natural gas (Johns Hopkins Bloomberg School of Public Health, 2015). Pennsylvania is the second highest shale gas producing state, primarily because of the Marcellus Shale formation which underlies approximately 60% of the state (Pennsylvania Independent Oil and Gas Association, n.d.; Tian et al., 2019). The Marcellus Shale is known to have unusually high concentrations of both uranium and radium (Tian et al., 2019).

Columbia County, Pennsylvania is one of the counties in the state that is most affected by radon. Columbia County's average radon test is 17.3 pCi/L, which is far greater than the 4 pCi/L action level and the average U.S. radon level of 1.3 pCi/L (Air Chek, n.d.; U.S. EPA, 2022). Though Columbia County faces extraordinarily high risk, the county demonstrates decreased testing behaviors compared to other counties in Pennsylvania, potentially as a result of less awareness of radon, financial barriers to testing, or both (Evans, 2016; Irvine et al., 2022). This results in a high level of testing disparity, a metric which combines both radon risk and testing frequency (Figure 3). Assessing testing disparity helps to identify locations that call for increased attention towards indoor radon (American Lung Association, 2022).

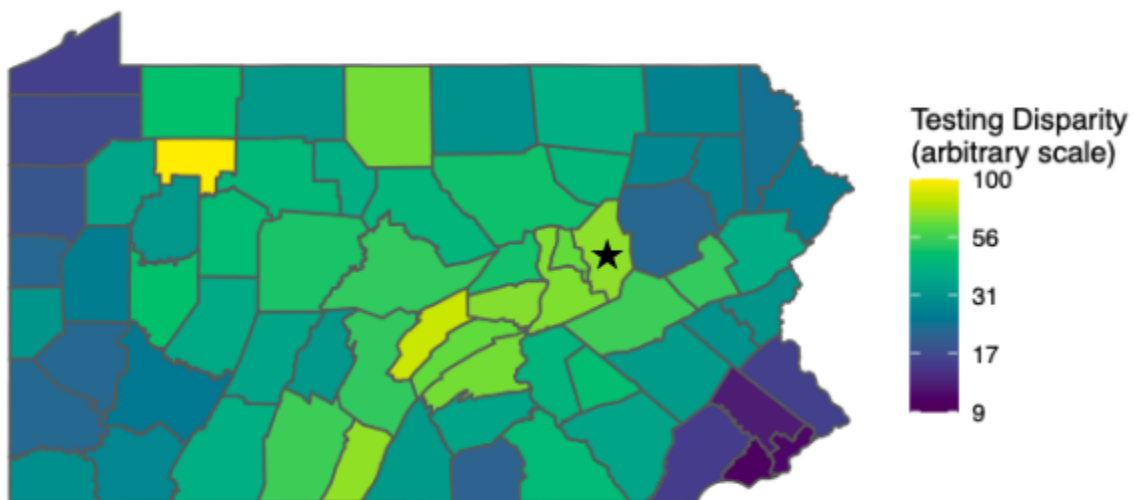


Figure 3. Radon testing disparity in Pennsylvania's counties. Columbia County is indicated by a black star. Image modified from the American Lung Association, 2022.

Increasing Radon Awareness

Currently, no map exists that quantifies the risk of indoor radon in Pennsylvania on a larger scale than county-by-county. In 1993, the U.S. EPA released a map of radon zones for the entire United States, though this map does not provide detailed enough information to determine which households or communities are at more risk to radon (U.S. EPA, 1993). The presence of indoor radon cannot be accurately predicted on a household by household basis, though there are ways to quantify the overall risk throughout a geographical area. One method is to produce a risk

index using a geographical information system (GIS) multi-criteria analysis. A multi-criteria analysis allows sites to be ranked based on how well they meet a series of criteria. This process can be applied to determine indoor radon risk for a designated area based on all relevant factors that contribute to the risk.

To contribute to awareness and education about indoor radon, a map was created that is accessible to the public via ArcGIS StoryMaps (<https://arcg.is/efmuX>) and demonstrates the risk of indoor radon throughout Columbia County, Pennsylvania. This map has two intended functions. The first is to educate homeowners about the risk of radon in their communities and encourage proactive testing behaviors. The second is to identify communities that may benefit from more targeted outreach and educational programs about indoor radon. It is well documented that radon is a serious environmental hazard with potentially fatal consequences. Still, there is limited awareness of this threat. The intended purpose of this risk analysis is to quantify the severity of this issue within Columbia County and motivate the county residents to learn about radon and get their homes tested. Further, this analysis develops a methodology to determine geographical radon risk that can be reproduced and applied to other counties both within and outside of Pennsylvania or on a statewide level.

Methods

Study Region

Columbia County, Pennsylvania has an area of 1258 km² and is located in the east-central part of the state (Britannica, 2011). This county has a population of just under 65,000 residents (United States Census Bureau, n.d.). The poverty rate of Columbia County in 2021 was 16.2%, slightly elevated in comparison to the national poverty rate which was 11.6% that same year (United States Census Bureau, n.d., 2022). For Columbia County residents 25 years of age and older, 24.8% have a bachelor's degree or higher, while that same statistic is 37.9% for the United States as a whole (United States Census Bureau, n.d., 2022). The geologic units found in the county are almost all sedimentary and range in age from Silurian (beginning ~443.8 Ma) to Pennsylvanian (ending ~298.9 Ma) in age (United States Geological Survey [USGS], n.d.).

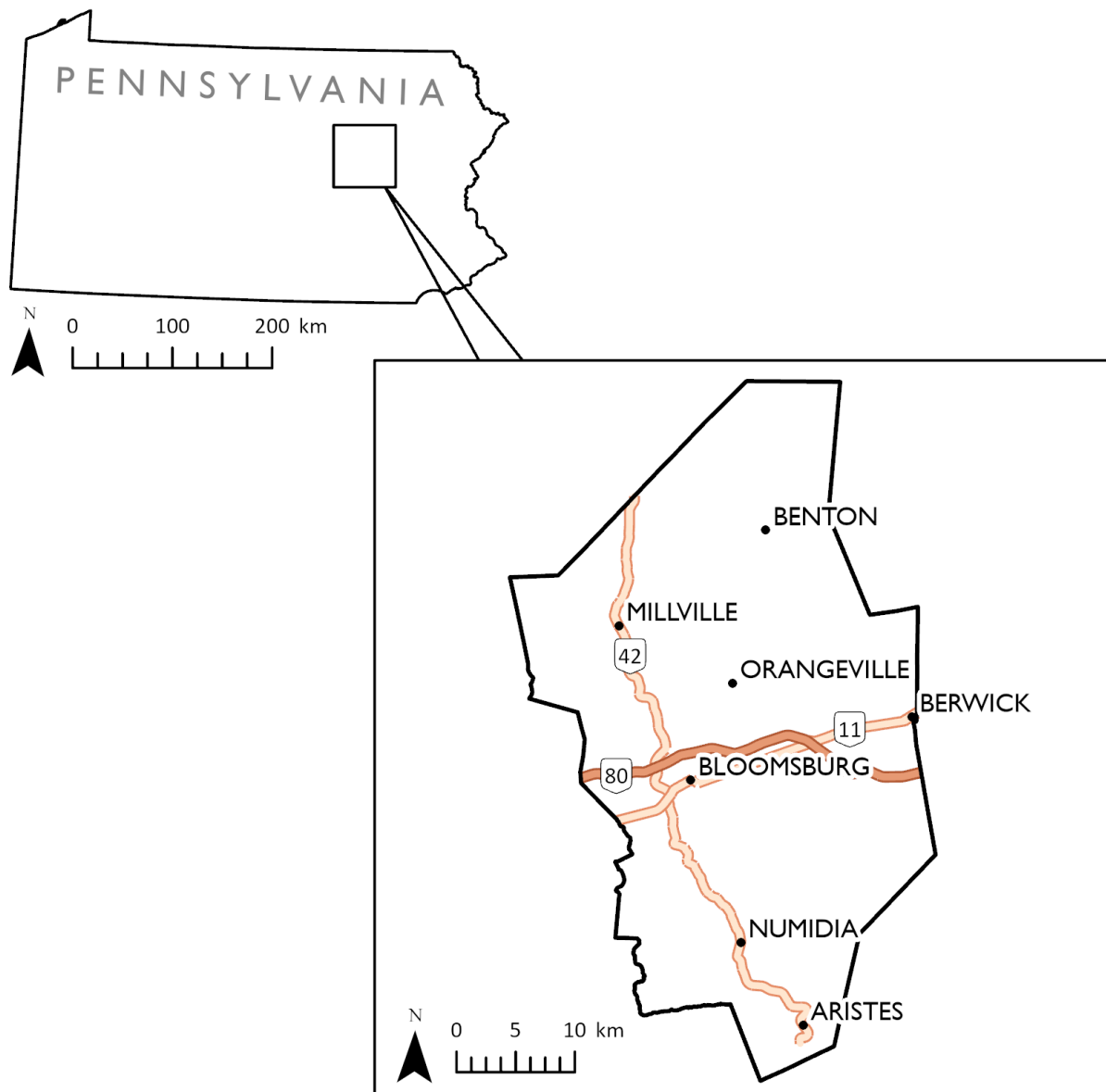


Figure 4. Study region map of Columbia County, Pennsylvania.

Input Variables

This risk analysis considered five input criteria that contribute to indoor radon risk. Some of these criteria are based on geologic factors, while others depend on the characteristics of structures within the county.

Lithology: The lithology of the bedrock underlying an area can pose a higher or lower risk of producing radon gas depending on its concentration of uranium (Churchill, 1991). Though almost all rocks contain some amount of uranium, certain types, such as intrusive igneous rocks, felsic igneous rocks, and flat-bedded deposits of sedimentary rocks (including black shales, coals, asphalts, and phosphate rocks) tend to have higher uranium concentrations (Ayotte et al, 2007; Churchill, 1991).

Soil Permeability: Soils contribute to radon risk both through their composition and their ability (or inability) to contain radon gas in the subsurface. Similarly to lithology, elevated uranium content of soil can increase its risk. However, this value has not been assessed for the vast majority of the soils in the county and is therefore unable to be considered in this analysis. Risk was assigned to each soil type based on its permeability, which is a key factor for determining how easily radon can escape from the ground. Highly permeable soils make it easier for radon that has decayed in the soil and underlying rock to pass through it, traveling to the surface and entering homes and other buildings (Churchill, 1991).

Proximity to Faults: Another geological factor that can increase levels of indoor radon are faults. Faults are defined as fractures between rocks that allow them to move relative to each other (USGS, n.d.). Faults increase radon risk because they provide pathways for radon to travel from within the ground to the surface. A recent study by the Eau Terre Environnement Centre found that homes that are located less than 150 meters from a major fault are more likely to have elevated radon levels (Drolet and Martel, 2016).

Water Supply: Buildings that use a private water supply, such as well water, were found to have on average a 21% higher concentration of indoor radon than those using municipal water (Johns Hopkins Bloomberg School of Public Health, 2015). Though private water supplies pose an elevated risk, it is still possible that public water supplies could also be contaminated because there is no standard requirement to test or treat them for radon (U.S. EPA, 2018).

Home Age: Newly-built homes tend to have higher levels of indoor radon. Radon concentrations were found to be higher in homes built from 2005-2019 compared to those built from 1800-2004 for all tested architecture styles. This can most likely be attributed to newer builds having increased air tightness that prevents contaminated air from leaving the home (Stanley et al., 2019). Beginning in the 1970s, homes have been built with increasing air tightness to reduce homeowners' gas and electricity bills, a direct response to the oil crisis of that decade (Cohen, 2004). This inhibits the amount of air circulation occurring and increases the likelihood that radon will remain in a home.

Table 1. Data sources for the input criteria.

Criteria	Originator	Dataset	Year Published
Lithology	United States Geological Survey	Geologic Units	2022
Soil Permeability	United States Department of Agriculture	Columbia County Soils	2022
Proximity to Faults	United States Geological Survey	Structures	2022
Water Supply	Pennsylvania Department of Environmental Protection	Public Water Supplier's Service Areas	2023
Home Age	U.S. Census Bureau	B25034: Year Structure Built	2020

Data Manipulation

This analysis utilized a GIS multi-criteria analysis methodology to create a risk index for indoor radon throughout Columbia County. A GIS multi-criteria analysis is a process used to evaluate many factors at once to gain information or answer questions about a geographical area (Tsihrintzis and Jain, 2010). GIS is used to perform these types of analyses because it allows for multiple sources of geographic data to be considered. Additionally, GIS is computer-assisted, allowing for faster and more accurate analysis and manipulation of geographic information. Though there are multiple methods that can be used to perform a multi-criteria analysis, the one best suited for the goals of this project is an analytical hierarchy process (AHP) and weighted linear combination (WLC) approach. AHP and WLC are used to first establish priorities within a criteria and then combine those criteria based on their relative importance. This method was chosen because AHP helps to minimize subjectivity while determining criteria weights and WLC allows for degrees of risk to be established.

The risk analysis was conducted using ArcGIS Pro 3.0.2 (Esri, 2022). Each of the input criteria layers were projected onto the North American Datum of 1983 (NAD 1983) Universal Transverse Mercator (UTM) Zone 18N coordinate system, which is a preferred projection for eastern Pennsylvania. The criteria were also converted to the raster data model with 25 meter x 25 meter resolution. This resolution was selected because it was small enough to preserve the detail of the features in the soil types layer, while not being excessively small which unnecessarily increases the size of the dataset. The input layers that included data beyond the scope of the county were clipped to the study region boundary. The fault line features were buffered to 150 meters to ensure they represented the full area of risk around them.

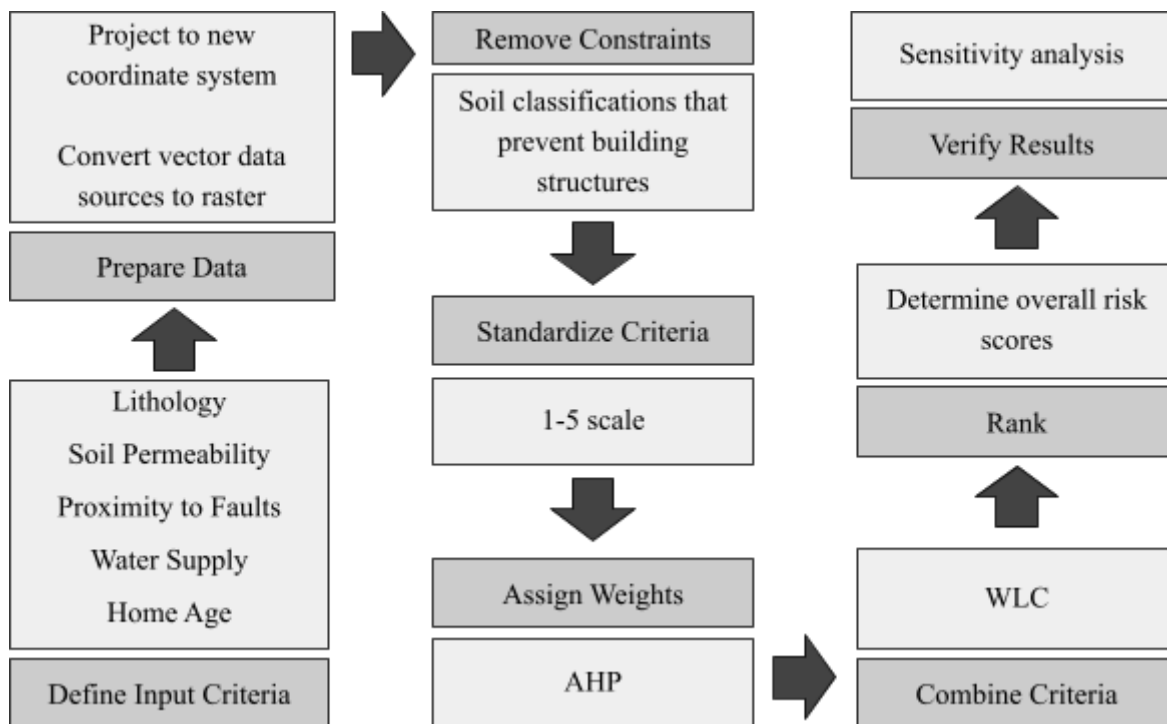


Figure 5. Workflow chart summarizing the process used to perform the risk analysis.

Standardize

The variables for each input criteria were assigned a radon risk score based on a 1-5 scale, with 1 being the lowest risk and 5 being the highest (Table 2). This was done to standardize the differing measurement units for each variable and ensure each criteria was ranked on the same ordinal scale. Some of the criteria contained qualitative data while others contained

quantitative. Establishing a standard ranking scale allows for these different types of data to easily be compared to each other and combined.

The method for assigning these ranks differed for each criteria. Assigning ranks to the various geologic units (the lithology criteria) was based on a literature review of documented uranium abnormalities present in the units. Uranium abnormalities occurring within Columbia County and in the surrounding counties were taken into account. This method was used because there are no quantitative measurements of uranium or radon for the majority of the geologic units in Pennsylvania. Given the scarcity of available research about uranium in Pennsylvania, the units found in Columbia County were ranked only using 1, 3, and 5. Additional information would be needed to further differentiate risk levels.

Soil permeability ranks were primarily assessed using a soil survey of Columbia County (Parrish, 1967). Supplementary sources were needed to assign ranks to more recently added soils that were not included in the 1967 survey. These sources primarily included soil surveys from nearby counties and the United States Department of Agriculture's National Cooperative Soil Survey (Broome County Soil & Water Conservation District, n.d.; Eckenrode, 1982; Fletcher, 1979; Kopas, 1982; Tornos, 1979; United States Department of Agriculture, 1992, 2021). In instances where a soil was described as having multiple rates of permeability (e.g., slow and moderately slow), the rank was assigned based on the more permeable of the two to account for the highest possible risk. In instances where the soil was described as having multiple layers with varying permeability (e.g., slowly permeable fragipan and moderately permeable overlying soil), the rank was assigned based on the most limiting, or least permeable, layer.

Proximity to faults and water supply each only had two possible ranks because of the limited alternatives within those criteria. There is only risk associated with the land within 150 meters of a fault, so areas that fell within that range were assigned a rank of 5 and areas that did not were assigned a rank of 1. The same principle was applied to the water supply criteria, but with ranks of 3 and 5. Areas that use a private water supply are known to have increased risk, and were assigned a rank of 5. Areas that use a public water supply are at a decreased risk, although not nonexistent, so they were assigned a rank of 3.

The home age criteria was ranked using the percentage of homes built after 1970 in each block group of the county. United States Census Bureau block groups were selected to divide the area because they were the smallest geographical areas that had available information about

when the structures were built. For this criteria, the ranks were matched to ranges of values established by Jenks natural breaks classification. Jenks classification was chosen because it identified natural patterns within the home age data, grouping together clusters of similar values (Esri, n.d). The block groups containing the highest percentages of homes built after 1970 were assigned a rank of 5, and the block groups containing the lowest percentages of homes built after 1970 were assigned a rank of 1.

Table 2. Ranking guidelines for each input criteria and their associated weights.

Rank	Criteria				
	Lithology	Soil Permeability	Proximity to Faults	Water Supply	Percent of Homes Built After 1970
5	High uranium content documented in Columbia County, PA	Rapid and very rapid	Within 150 meters	Private water supply	67.7-84.4
4		Moderately rapid			56.3-67.6
3	High uranium content documented in surrounding counties OR contains secondary uranium	Moderate		Public Water Supply	36.6-56.2
2		Moderately slow			18.8-36.5
1	No documented uranium abnormalities	Slow and very slow	Outside of 150 meters		5.2-18.7
Weight	31.1%	29.5%	15.6%	15.6%	8.3%

Constraints

Certain soil features were unable to be assigned a meaningful risk score and were excluded from consideration in the analysis. The soil classifications that were made into constraints were types of land uses, such as dams and impoundment structures, gravel pits, mine dumps, miscellaneous water, quarries, riverwash, coal settling basins, strip mine spoils, and water, that made it highly improbable for a structure to be built on top of them. Rather than being assigned a score of 1-5, the listed features were assigned a score of -999. This ensured that when all of the input criteria were combined, the constrained areas would have a large negative score that could easily be differentiated from the areas still in consideration.

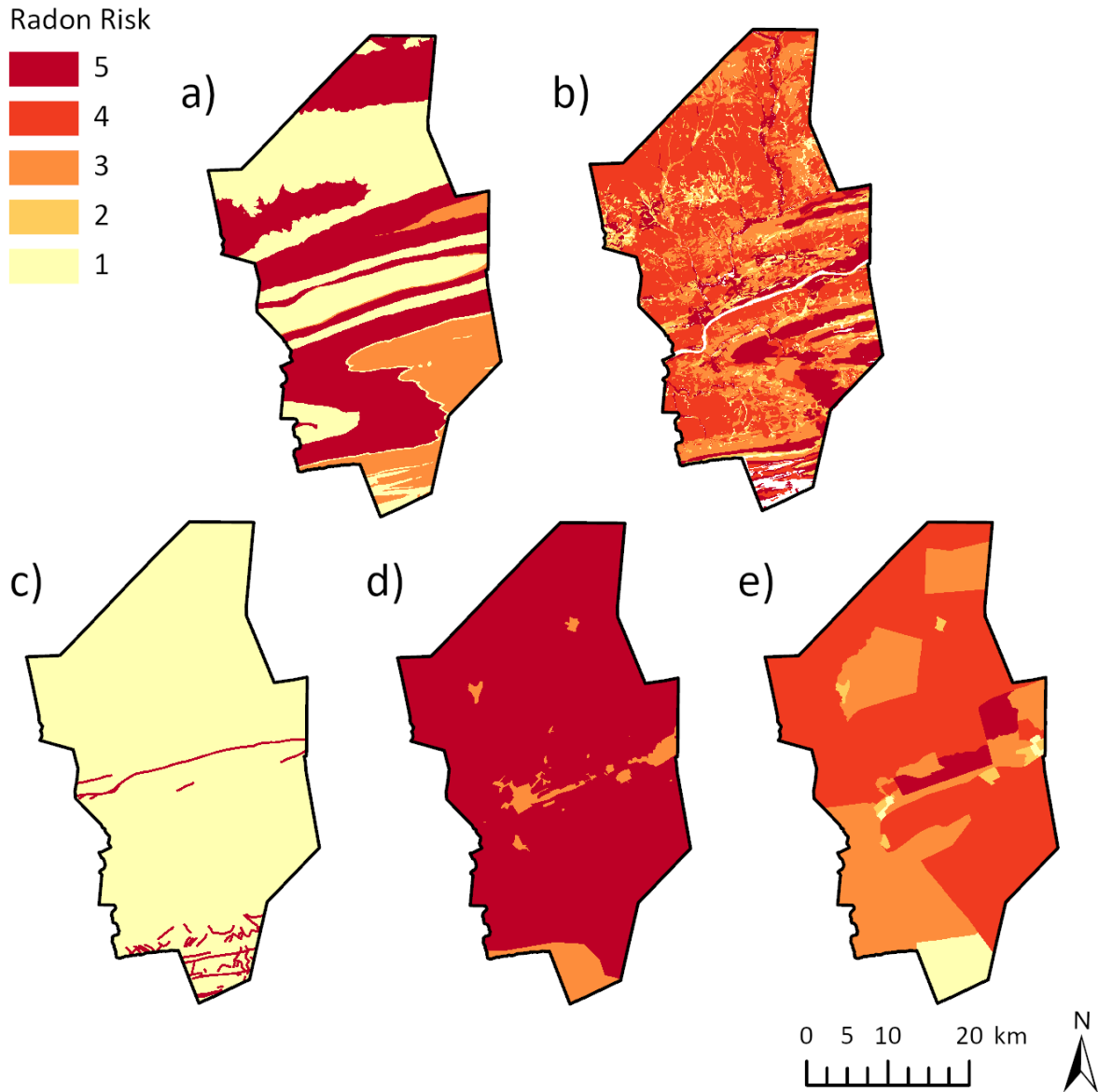


Figure 6. Ranked input criteria maps for a) lithology, b) soil permeability, c) proximity to faults, d) water supply, and e) home age.

Weight

The weight for each criteria was determined using an analytical hierarchy process (AHP) (Saaty, 1980). AHP helps to determine the relative importance of each criteria using a 1 to 9 ranking system of one criteria compared to another, creating a pairwise comparison matrix (Tables 3 and 4). A ranking of 1 suggests that both criterias are equally relevant to the analysis, while a score of 9 suggests that the first criteria is significantly more important than the second

(Duc, 2006). Pairwise comparison facilitates the comparison of only two factors at a time, which helps to minimize subjectivity and ensure consistency in the weighting process. An AHP consistency ratio was calculated to ensure that the decisions made in the pairwise comparison were logical and followed consistent reasoning (Table 4). A consistency ratio under 0.1 indicates that the weighting was consistent, with lower values indicating increased consistency (Wedley, 1993).

Table 3. Pairwise comparison 1-9 ranking scale.

Importance	Definition
1	Equal Importance
3	Somewhat more important
5	Definitely more important
7	Much more important
9	Very much more important
2, 4, 6, 8	Intermediate values

Table 4. AHP comparison matrix used to calculate the weights of input criteria.

Criteria	Lithology	Soil Permeability	Faults	Water Supply	Home Age
Lithology	1.00	1.00	0.50	0.50	0.25
Soil Permeability	1.00	1.00	0.50	0.50	0.33
Faults	2.00	2.00	1.00	1.00	0.50
Water Supply	2.00	2.00	1.00	1.00	0.50
Home Age	4.00	3.00	2.00	2.00	1.00
Consistency Ratio: 0.002					

Combine

Input criteria were combined using a weighted linear combination (WLC). This is a technique that requires all criteria be assigned to the same numeric scoring system and then combined using a weighted average (Tsihrintzis and Jain, 2010). Equation (1) demonstrates this process.

$$A_i = \sum_{j=1}^n W_j X_{ij} \quad (1)$$

In this equation, A_i is the score assigned to each piece of land, W_j is the weight of the criterion, and X_{ij} is the rank location i received in reference to the criterion j . The total number of criteria is represented by n and $j=1$ indicates that all criteria weights should sum to 100%. Higher values of A_i indicate the criteria are being matched more closely (Shahabi et al., 2014). An advantage of this approach is that both qualitative and quantitative data can be considered at the same time. For example, a qualitative value of lithology and a quantitative value of the percent of homes built after 1970 can both be factors in the same analysis. In this analysis, the five input criteria were combined using the weights generated by AHP (Table 2).

Visualization of Results

The scores calculated in the WLC process were grouped into five classes using Jenks natural breaks classification to allow final radon risk scores of 1-5 to be assigned to each division of land. The Jenks classification method finds natural breaks in the data and clusters together groups of similar values. Jenks was used to classify the final risk scores because it creates classes that are meaningful to the patterns found in the data and allows for like values to be kept together (Esri, n.d.). Ideally, a quantile distribution method would have been used to classify the data. A quantile distribution places an approximately equal amount of features in each class, so each risk score would correspond to a set amount of area (five ranks each making up 20% of the area of Columbia County), and may make it easier for a general audience to interpret the map. However, this approach was not possible because of the distribution of data. There were a large number of data points with the same values, preventing those values from being split into different classes and making a true quantile distribution impossible.

Sensitivity Analysis

A sensitivity analysis is a procedure used to examine the influence of the input criteria on the final output of a model (Chen et al., 2010). For an AHP/WLC analysis, this helps reveal how the weights of each criteria affect the final risk map. A sensitivity analysis can provide confidence in the results of the model if similar areas of risk appear despite changing the weights of the criteria. To verify the results of this analysis, two additional weighted linear combinations were run (Table 5). The first alternative weighting approach weighed each input criteria equally, which simulates the result of each criteria having an equally important contribution to radon risk.

The second weighting approach used was inverting the weights determined by AHP (e.g. the highest weight variable was assigned the percentage of the lowest weight variable, the second highest weight variable was assigned the percentage of the second lowest weight variable, and so forth). The risk maps using equal weights and inverted weights were symbolized using Jenks natural breaks classification to replicate the methods used to produce the original risk map. The outputs of these two additional weighted linear combinations were then compared to the output of the original risk map to determine which areas of high and low risk remained consistent and how the percentage of land covered by each risk score changed.

Table 5. Weights assigned to each criteria for the various sensitivity analysis models.

Criteria	AHP Weight	Equal Weight	Inverted Weight
Lithology	31.1%	20.0%	8.3%
Soil Permeability	29.5%	20.0%	15.6%
Proximity to Faults	15.6%	20.0%	15.6%
Water Supply	15.6%	20.0%	29.5%
Percent of Homes Built After 1970	8.3%	20.0%	31.1%

Results

Risk Analysis

The risk analysis produced indoor radon risk scores for Columbia County, Pennsylvania (Figure 7). After removing constraints, 95.8% of the study region was eligible to receive a risk score. The constrained areas primarily fall towards the southern tip of the county and are also noticeable where the Susquehanna River cuts northeast to southwest through the center of the county. The areas of highest overall risk are spread throughout the area, often appearing in linear bands that stretch from the western to eastern borders. The lowest overall risk scores similarly appear in east-west oriented bands that alternate with the highest risk areas. In these bands of lower risk, there are very few small high risk areas scattered throughout, except in the southernmost part of the county. The high risk areas are somewhat less uniform and tend to have small inclusions of moderate risk areas within them. The most prominent high risk zones are at the northern tip, surrounding the town of Millville in the northwestern region, in an east-west band north of I-80, and covering the majority of area below the Susquehanna River. The most

prominent low risk zones include the area surrounding Benton in the north, the area directly north and south of I-80, and the southern tip.

The maximum risk value produced in this analysis is 4.917 out of a possible 5 points. The minimum risk value is 1.312 with a lowest possible value of 1. The average risk score is 3.288 and the standard deviation is 0.600. High risk areas (defined as having risk scores of 4 and 5) are slightly more dominant and cover a combined 48.3% of the county's area, while low risk areas (defined as having risk scores of 1 and 2) cover a combined 37.0% of the county (Table 6).

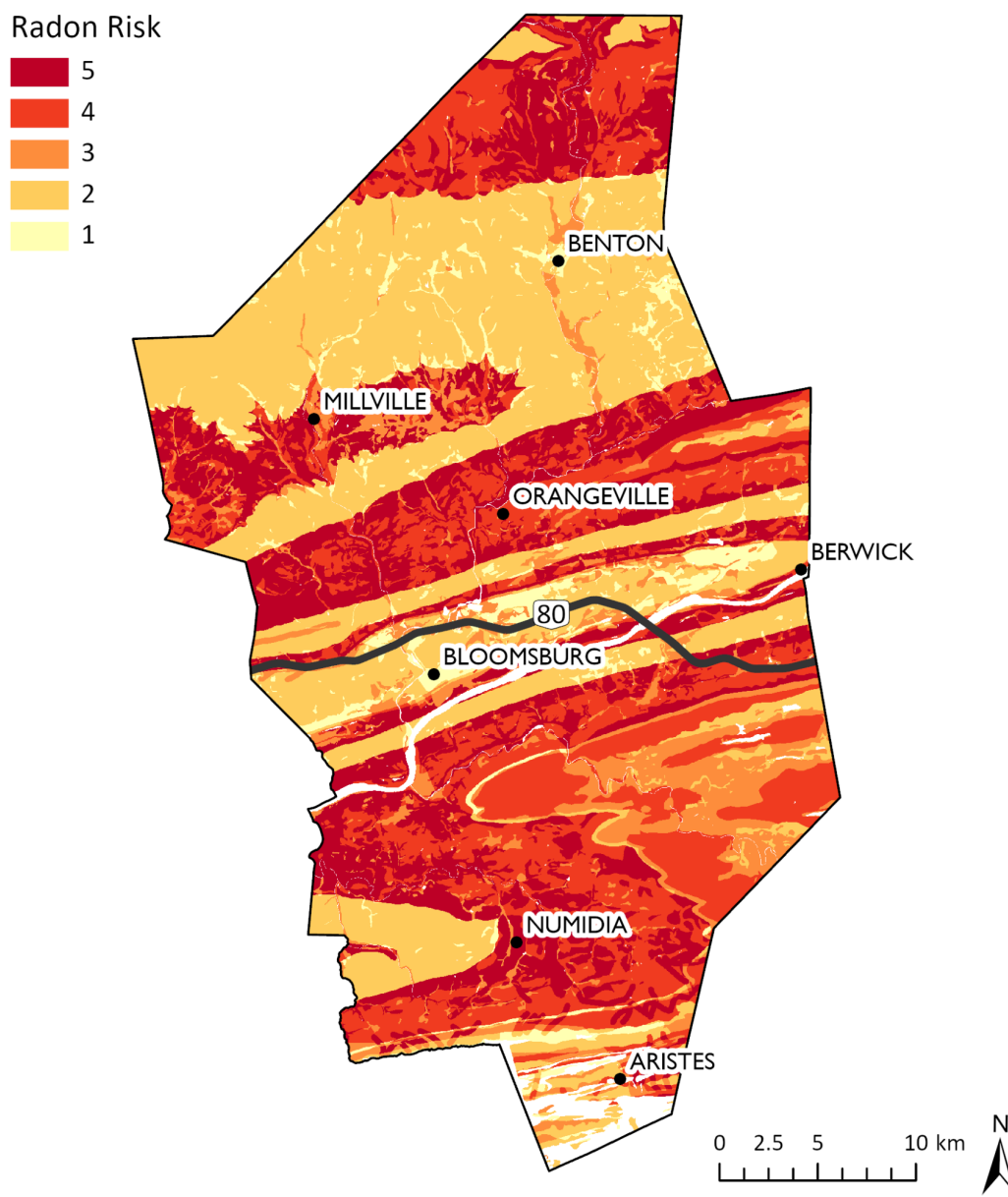


Figure 7. Indoor radon risk index for Columbia County, Pennsylvania.

Table 6. The final risk scores and their corresponding range of WLC values along with the amount and percentage of study region area assigned to each risk score.

Risk Score	Score Range	Area (km ²)	Percent of Study Region Area
5	3.815-4.917	293.3	22.8
4	3.391-3.814	328.51	25.5
3	2.882-3.390	134.17	10.4
2	2.387-2.881	420.61	32.7
1	1.312-2.386	55.0	4.3
Constraint		54.63	4.2

Sensitivity Results

The sensitivity analysis identified areas of high and low risk that remained consistent regardless of how the input criteria were weighted (Figure 8). Consistent areas of high risk include the northern tip, the area in the northwest surrounding Millville, the band north of I-80 that stretches from the western to eastern edge, and most of the area below the Susquehanna River besides the southern tip of the county. Consistent areas of low risk include the southern tip and some of the land just north of the Susquehanna River. The original risk map has a significantly larger percentage of low risk (level 1 and 2) areas than both the equal and inverted weights maps, but a lesser percentage of moderate (level 3) risk. The original and equal weights maps have similar percentages of high risk (level 4 and 5) areas, though that percentage increases significantly in the inverted weight map (Table 7).

Table 7. The percent of area covered by each risk score in the sensitivity analysis models.

Risk Score	Percent of Study Region Area		
	AHP Weights	Equal Weights	Inverted Weights
5	22.8	16.0	20.0
4	25.5	33.4	46.6
3	10.4	29.3	20.5
2	32.7	15.7	6.0
1	4.3	1.4	2.8
Constraint	4.2	4.2	4.2

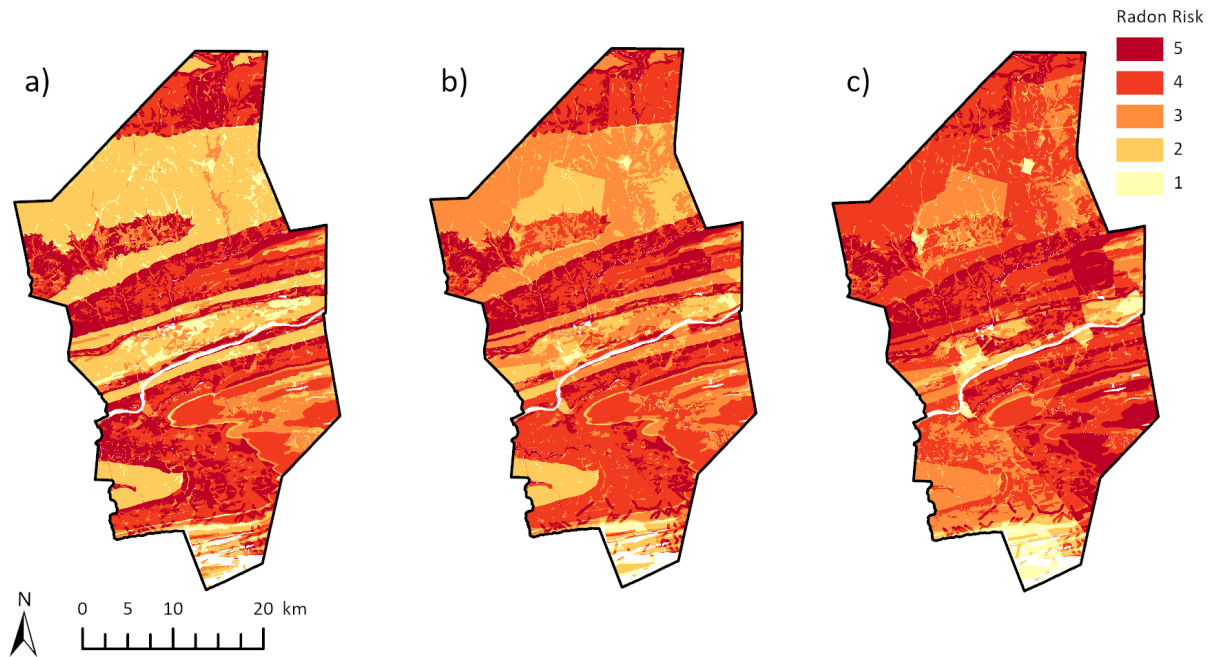


Figure 8. The risk maps with a) weights determined by AHP, b) equal weights, and c) inverted weights.

Discussion

Interpretation of Results

Columbia County, Pennsylvania has been identified as an area that consistently faces higher levels of indoor radon (American Lung Association, 2022). The risk index established in this study helps identify geographic areas of overlap between risk factors to highlight regions of the county that face more risk than others. Some of the largest cities in Columbia County are placed on the risk index in Figure 5. Bloomsburg is the largest city in Columbia County with a population of 12,597 (United States Census Bureau, n.d.). Fortunately for its residents, Bloomsburg is located in a risk 1 zone, which is the lowest possible score and only covers 4.3% of the county. Berwick Borough, the second most populated place in Columbia County with 10,349 residents, is located in a risk 4 zone (United States Census Bureau, n.d.). This suggests that people living in Berwick may want to consider more frequent radon testing. Additional populated places not shown in Figure 7 are featured on the story map so that Columbia County residents viewing the map can more easily locate their own neighborhood and assess their risk.

The risk index also helps to confirm and explain why Columbia County's average radon test level is far greater than the EPA's action level. Almost half of the county has a combination

of risk factors that qualify it as high risk. Less than 5% of the area is classified as the lowest risk level and the average risk score is a level 3. These three pieces of information explain why so many homes in the county test higher for radon. Looking at the criteria that contribute to radon risk, Columbia County faces a unique combination of conditions that put it at risk, including that there is high uranium in multiple geologic units, the majority of homes rely on a private water supply, most of the land is covered by rapidly permeable soils, and many homes were built after 1970 (Figure 6). The risk analysis agrees with what is already known about Columbia County's risk and offers specific insights as to what is causing it.

When considering the impact of the individual criteria on the final risk index, it seems that the lithology of the geologic unit underlying a given area had the largest influence. The linear bands of high and low risk in the final risk index seem to be a product of the lithology input criterion (Figures 6 and 7). Though this can partially be attributed to its high weight (31.1%), these bands are still visible in the sensitivity analysis when all criteria were weighted equally and are even somewhat visible when the weights were inverted and lithology had the lowest weight (Figure 8). This indicates that the blocks of high and low risk are not a result of improper weighting and are more likely caused by the lithology features being ranked only using 1, 3, and 5. This creates a stark difference when a geologic unit ranked 1 and a unit ranked 5 are located next to each other, as the majority in Columbia County are (Figure 6).

Radon Awareness and Education

The final product of this analysis is an ArcGIS Story Map (<https://arcg.is/efmuX>) that is available online to the public. The story map guides the viewer through an interactive experience that presents the risk index and shares information about indoor radon. The text that accompanies the map describes what radon is, explains the related health concerns, and provides links to resources such as free radon test kits and educational videos. Engagement with the map can be measured over an extended period of time using the view count provided on the story map.

Limitations

A challenge faced while creating the risk index was the lack of quantitative information available about the uranium concentrations in the geologic units and soils of the county. This required that these two criteria had to be evaluated based on qualitative descriptions rather than

measurements. This posed the biggest issue for the lithology criteria because subjectivity was introduced into the ranking process. Despite a thorough review of publications about uranium and radon in the units, it was still difficult to determine how to rank descriptions of uranium abnormalities on a numerical scale. It also would have been ideal to know how much uranium was present in each soil type in the county, though soils were still able to be evaluated as a criterion because of the availability of information about their permeability.

A limitation of the final risk map is possible adverse interpretations by viewers. The story map is intended to motivate Columbia County residents to learn more about radon and encourage them to test their homes. However, the opposite effect may be produced for viewers living in a low risk area. They may interpret the map to mean that because their homes are in a low risk zone, they do not need to test for radon. The story map format was chosen to help combat this. The text alongside the map explains that a lower risk score does not imply a complete absence of radon risk. The text also states that Columbia County as a whole has an unusually high radon risk and that every resident, regardless of their home's location on the map, should consider radon testing. The yellow, orange, and red color scheme used to symbolize the final risk scores may also be a visual cue to viewers that the risk is not nonexistent in some areas, as a color scheme such as green to red may suggest. Even with these measures taken, the map may still be interpreted in unintended ways.

Comparable Studies

GIS multi-criteria analysis is a well-established approach for scoring land based on multiple factors. It has often been applied to evaluate risk and, more specifically, is a common tool for evaluating geologic hazards, as done in this analysis. Nyimbili et al. (2018) used a similar approach to model earthquake risk in the Küçükçekmece district of Istanbul, Turkey. They examined five criteria, including topography, distance to epicenter, soil classification, liquefaction, and fault/focal mechanism. Combining weights established by AHP and the technique for order preference by similarity to ideal solution (TOPSIS), they produced a series of risk maps that established areas of risk, ranked 1-4, throughout the district.

Feizizadeh and Blaschke (2011) performed a GIS multi-criteria analysis to assess landslide risk in Bostan-Abad County, Iran. They based their analysis on criteria relating to geological, environmental, and human factors, which included distance to streams, distance to

roads, aspect, slope, lithology, distance to faults, precipitation, and land use. This was also an AHP-based analysis, and was used to produce a landslide susceptibility map with four final risk ranks. GIS multi-criteria analysis is a useful tool for solving many problems requiring multiple sources of geographic data. It has proven especially effective and applicable for assessing risk of geologic hazards, as seen in Nyimbili et al. (2018), Feizizadeh and Blaschke (2011), and countless others.

Suggestions for Future Study

Columbia County is only the first of many potential applications of this methodology. Multiple other areas throughout Pennsylvania face high radon risk and demonstrate decreased testing behaviors. Two of the counties that meet these conditions are Forest and Mifflin, which would be natural next locations to implement this methodology. It may also be beneficial to look beyond Pennsylvania to other states that have even higher radon levels and testing disparity. These include North Dakota, South Dakota, Montana, and Ohio (American Lung Association, 2022). Though these areas demonstrate greater need than others, any community can benefit from increased radon education.

If this methodology is applied in other regions of the United States or abroad, it may be beneficial to consider additional input criteria that are regionally significant, such as seismic zones or areas of geothermal activity. These factors influence radon risk but were not considered in this analysis because of their minimal relevance to Pennsylvania (Churchill, 1991). If this methodology were to be applied elsewhere, the input criteria should be modified as needed to support the unique conditions of each study region.

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