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TIME SERIES ANALYSIS OF RADON CONCENTRATION AT DIFFERENT DEPTHS IN AN UNDERGROUND GOLDMINE

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ABSTRACT

Indoor radon concentrations were collected monthly over a period of one year in 10 different levels in an underground goldmine and the data was analysed using a four moving average time series to determine the relationship between depths of the underground mine and the indoor radon concentration. The detectors were installed in batches within four quarters. The measurements were carried out using LR115 solid state nuclear track detectors. Statistical models are applied in the prediction and analysis of the radon concentration at various depths. The time series model predicted a positive relationship between the depth of the underground mine and the indoor radon concentration. Thus, elevated radon concentrations are expected at deeper levels of the underground mine, but the relationship was insignificant at the 5% level of significance with a negative adjusted R^2 ($R^2 = -0.021$) due to an appropriate engineering and adequate ventilation rate in the underground mine.

Keywords: LR115, Radon Concentration, Time Series, Underground goldmine,
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Introduction

Radon is a naturally occurring radioactive noble gas. It is part of the natural decay series of uranium (U) and thorium (Th) found in all soils and rocks to a varying concentration. There are three radioisotopes of radon naturally present in the environment: Radon-222 from the uranium-238 decay series, radon-220 from thorium-232 decay series and radon-219 from uranium-235 decay series. Radon-219 is of low radiological significance because of its short half-life of 4 seconds and uranium-235 represents a small percentage (0.3%) of the activity of natural occurring uranium (Biira, Kisolo, & D'ujanga, 2014). While the concentration of thorium-232 in the environment is comparable or higher than that of uranium-238, the relatively shorter half-life (56 seconds) of radon-220 compared to radon-222 with half-life (3.82 days), makes radon- 222 more important. This is so because radon-222 can migrate over much greater distances after production than radon-220. Therefore radon-222 produced in the soil is the principal source of radon concentration in buildings or walls of mines and in both indoor and outdoor air, while radon-220 is of concern from a radiation protection view point if the concentration of thorium-232 is high (A. Nero Jr, 1985; A. V. Nero Jr, 1990). In nature, mining involves the production of large quantities of waste, which may contaminate soils over a large area, thereby negatively impacting the environment and human health (Munyaradzi, Anna, & Makondelele, 2018). Mining is one of the major causes of elevation of NORMs concentrations on the earth's surface causing health risks to humans, especially when inhaled or ingested (Rowland, 1993).

This paper is based on a statistical model using trend equations to extrapolate radon concentration at different levels below the reference level in the underground goldmine.

Materials and Methods

The radon gas measurement was done using radon samplers made up of LR-115 (type II strippable) cellulose nitrate detectors manufactured by Kodak Pathé in France and 25 cm PVC pipe with a diameter of 50 mm and an end cap. The detectors of area 2cm × 2cm were attached to a plastic dish with its sensitive side facing upwards and covered with a perforated plastic dish. The plastic dish with the radon detectors were installed at ten different locations of the Subika underground mine. The detectors were planted in batches within the four quarters. Each batch within the quarters was left within the sampling points for approximately four (4) weeks.

Forty (40) sampling points within the ten randomly selected points were chosen within the project site using a non-probability quota sampling. A total number of 40 dishes containing 80 detectors were deployed at the points for each batch (month). In all a total number 320 detectors were deployed at the sampling points of which 20 of them were crushed by the heavy-duty vehicles underground leaving at total of 300 detectors to be analysed at the Nuclear Track detection Laboratory of the Ghana Atomic Energy Commission.

After exposure for one (1) month, the detectors were removed from the dish. 200 grams of sodium hydroxide pellet was weighed in a beaker with an electronic balance and the solution prepared in a 2L volumetric flask using a magnetic stirrer at the Nuclear Track detection Laboratory of the Ghana Atomic Energy Commission. The detectors were then subjected to chemical etching in a 2.5 M analytical grade sodium hydroxide solution at (60 ±1) ºC, for two hours in a constant temperature water bath to enlarge the latent tracks produced by alpha particles from the decay of radon. After the etching, the detectors were washed with running cold water for 20 minutes to stop the etching process, then washed in distilled water for 15minutes. The detectors were then peeled whilst in the distilled water and air dried on a cardboard. After a few minutes of drying in the air, the detectors were ready for track counting.

The counting of tracks and the image acquisition was performed using a commercial scanner (Epson Perfection V600 Photo) having 4800`x9600-dpi resolution and 48-bit for colour and 16-bit for grey maximum depth coupled to a laptop. An important characteristic of the scanner is its double-lighting system. The films were inserted between two rigid transparent sheets on the scanner surface. This arrangement provides a reasonably uniform illumination of the films, reducing the formation of folds and/or bubbles. The negative acquisition of the film image was carried out using 24-bit colour depth and 4800-dpi resolution. This choice produces an image that allows discerning appropriate tracks without requiring too much memory. A square area (1x1) cm^2 inside the exposed surface of the film was acquired. ImageJ (Image Processing and Analysis in Java), a free digital image-processing software developed by the National Institutes of Health of the United States was used for the image processing and calculation of Radon concentration.

Time Series Analysis using Trend equation model.

The time series analysis using moving averages was used to forecast and predict radon concentrations underground at a particular depth. The time series analysis reduces the error or assumes a more perfect linear relationship since it reduces fluctuations as seen figure 1.

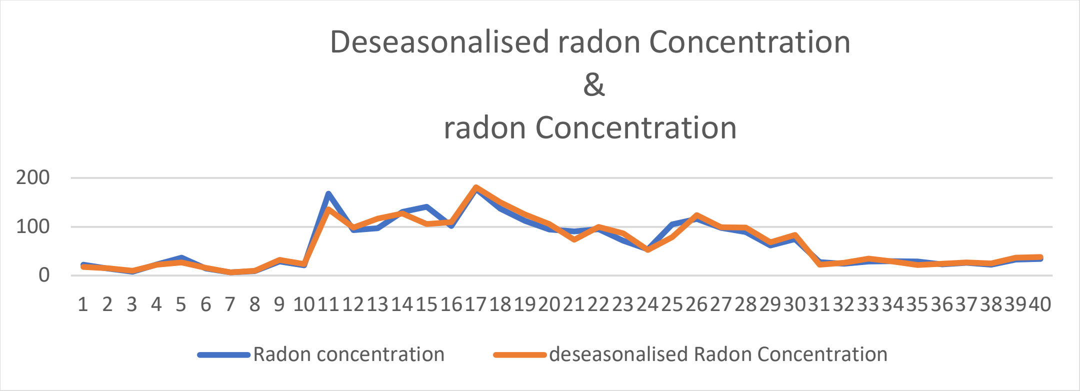

Figure 1: Graph of Deseasonalised of radon concentration and radon concentration.

A time series is a collection of data for some variable. The purpose of time-series analysis is to predict or forecast future values of the variable from past observations.

The least square method is used to describe the equation for the trend of radon concentration at different depth.

The trend equation is given by

$$y = a + bx \tag{1}$$

Where

y = The projected value of the Y variable for a selected value of x.
a = The Y – intercept and it's the estimated value of Y when x = 0
b – the gradient or the slope of the line or the average change in Y for each change of one unit in x.
x = any value of depth that is selected.

Assumptions for the model

1. The line of best fit assumes that there exists a linear relationship between the dependent variable (Radon Concentration) and independent variables (depth of levels from reference points).

   This model assumes that the line of best fit is derived by minimizing the deviations of the points of the pair data from the line of regression.

   In the case of this research the trend equation will be modified as $y = a + bx$

   $$a = \frac{\Sigma y - b\Sigma x}{n} \qquad b = \frac{n\,\Sigma xy - \Sigma x\Sigma y}{n\Sigma x^2 - ((\Sigma x)^2)} \qquad (2)$$

   where y = Radon Concentration b= regression coefficient x = depth from reference level

   These values are substituted into the equation $y = a + bx$ to obtain the trend equation using SPSS.

   Results from regression analysis may be used for forecasting and predictions of the radon concentration at different depths.
2. To ascertain the reliability of the trend equation for making predictions interpolation (Prediction within the observed values of the dependent variables) and extrapolation (Prediction outside the observed values of the dependent variables) is used, in the case of interpolation the reliability of the model can be guaranteed. Extrapolation predictions can't be guaranteed hence must be treated with caution.
3. The coefficient of determination is used to determine the proportion or the percentage of the error or variation in the dependent variable 'explained' by the variation in the independent variable) using the Pearson's correlation coefficient.

Results and Discussion

Time Series Model

Radon concentrations and distances form the reference level to generate a linear regression model for forecasting and prediction of radon concentration at deeper levels or distances in the underground mine using the moving average trend analysis in time series was calculated using table 1.

Table 1: Time Series Moving averages.

Quarter	Levels	Distance below Reference level [1000-levels(m)]	Radon Concentration (Bq/m^3)	Four Q Moving Total quarter	Four Quarter Moving Average	Centred Moving Average	Ratio-to- Moving Average
			I	II	III=II/4	A=III1+III2/2	IV=I/A
I	YOD 1000	0	22.69				
	SKY DEC 1000	0	14.37				
				68.53	17.13		
	YOD 960	40	8.39	82.59	20.65	18.89	0.4442
	YOD 920	80	23.08	82.93	20.73	20.69	1.1155
	YOD 880	120	36.75	81.44	20.36	20.55	1.7886
	YOD 840	160	14.71	67.84	16.96	18.66	0.7883
	SKY ACCN 820	180	6.9	60.06	15.02	15.99	0.4316
	YOD 810	190	9.48	66.62	16.66	15.84	0.5987
	EMP 800	200	28.97	227.58	56.90	36.78	0.7878

	EMP 790	210	21.27	311.68	77.92	67.41	0.3155
II	YOD 1000	0	167.86	379.76	94.94	86.43	1.9421
	SKY DEC 1000	0	93.58	489.23	122.31	108.62	0.8615
	YOD 960	40	97.05	462.42	115.61	118.96	0.8158
	YOD 920	80	130.74	470.49	117.62	116.61	1.1211
	YOD 880	120	141.05	551.12	137.78	127.70	1.1045
	YOD 840	160	101.65	557.47	139.37	138.57	0.7335
	SKY ACCN 820	180	177.68	528.51	132.13	135.75	1.3089
	YOD 810	190	137.09	521.32	130.33	131.23	1.0447
	EMP 800	200	112.09	434.77	108.69	119.51	0.9379
	EMP 790	210	94.46	392.85	98.21	103.45	0.9131
III	YOD 1000	0	91.13	352.50	88.13	93.17	0.9781
	SKY DEC 1000	0	95.17	311.96	77.99	83.06	1.1458
	YOD 960	40	71.74	326.05	81.51	79.75	0.8995
	YOD 920	80	53.92	346.77	86.69	84.10	0.6411
	YOD 880	120	105.22	372.48	93.12	89.91	1.1703
	YOD 840	160	115.89	408.40	102.10	97.61	1.1873
	SKY ACCN 820	180	97.45	364.79	91.20	96.65	1.0083
	YOD 810	190	89.84	323.47	80.87	86.03	1.0443
	EMP 800	200	61.61	254.06	63.52	72.19	0.8534
	EMP 790	210	74.57	188.80	47.20	55.36	1.3471
IV	YOD 1000	0	28.04	156.18	39.05	43.12	0.6502
	SKY DEC 1000	0	24.58	111.56	27.89	33.47	0.7344
	YOD 960	40	28.99	112.49	28.12	28.01	1.0351
	YOD 920	80	29.95	110.70	27.68	27.90	1.0735
	YOD 880	120	28.97	108.01	27.00	27.34	1.0597
	YOD 840	160	22.79	100.63	25.16	26.08	0.8738
	SKY ACCN 820	180	26.3	104.65	26.16	25.66	1.0249
	YOD 810	190	22.57	115.99	29.00	27.58	0.8183
	EMP 800	200	32.99				
	EMP 790	210	34.13				

Table 2: Seasonal Index

Quarter	I a	II b	III c	IV d	Mean Ratio *B=Average of a,b,c,d*	Seasonal Index *Normalizing ratio (0.96) ×B*
YOD 1000	0	1.942149717	0.978117663	0.650240594	1.19	1.24
SKY DEC 1000	0	0.861505886	1.145832706	0.734443863	0.91	0.95
YOD 960	0.444150344	0.815846162	0.899547029	1.035126088	0.80	0.83
YOD 920	1.115514741	1.121137087	0.64112244	1.073524799	0.99	1.03
YOD 880	1.788647563	1.104531083	1.170330205	1.059668054	1.28	1.33
YOD 840	0.788317256	0.733544412	1.187275894	0.873849693	0.90	0.93
SKY ACCN 820	0.431587177	1.308900716	1.00829033	1.024941543	0.94	0.98
YOD 810	0.598673824	1.044664374	1.044256531	0.818346628	0.88	0.91
EMP 800	0.787763426	0.937903335	0.853427528	0	0.86	0.89
EMP 790	0.315543523	0.913076049	1.347062277	0	0.86	0.89
TOTAL					9.61	10.00

- The mean ratio moving average is computed by averaging the ratio –to – moving average of each quarter for every level.
- The mean ratios and are then summed, theoretically it was expected sum up to 10.00 (since the data is for 10 levels) but due to moving and averaging, the mean ratio summed up to 9.61.
- To obtain the seasonal index the mean ratio for each level is normalized by using the factor obtained from dividing 10 by the sum of the mean ratio 0.96 (9.6/10 = 0.96). This result is referred to as the normalization ratio or correction factor. This normalization ratio is then multiplied by each of the mean ratio to obtain the seasonal index for each level.
- Deseasonalised radon concentration is measured by dividing the radon concentration by the seasonal index in table 3.

Table 3: De Seasonalised Radon Concentration

Levels	Distance below Reference level (Depth) [1000-levels(m)]	Radon Concentration (Bq/m^3) I	Seasonal Index II	Deseasonalized Radon conc III = I / II
YOD 1000	0	22.69	1.24	18.32
SKY DEC 1000	0	14.37	0.95	15.11
YOD 960	40	8.39	0.83	10.10
YOD 920	80	23.08	1.03	22.45
YOD 880	120	36.75	1.33	27.57
YOD 840	160	14.71	0.93	15.78
SKY ACCN 820	180	6.9	0.98	7.03
YOD 810	190	9.48	0.91	10.39
EMP 800	200	28.97	0.89	32.38
EMP 790	210	21.27	0.89	23.81
YOD 1000	0	167.86	1.24	135.54
SKY DEC 1000	0	93.58	0.95	98.40
YOD 960	40	97.05	0.83	116.77
YOD 920	80	130.74	1.03	127.19
YOD 880	120	141.05	1.33	105.83

YOD 840	160	101.65	0.93	109.05
SKY ACCN 820	180	177.68	0.98	180.99
YOD 810	190	137.09	0.91	150.31
EMP 800	200	112.09	0.89	125.30
EMP 790	210	94.46	0.89	105.73
YOD 1000	0	91.13	1.24	73.58
SKY DEC 1000	0	95.17	0.95	100.07
YOD 960	40	71.74	0.83	86.32
YOD 920	80	53.92	1.03	52.45
YOD 880	120	105.22	1.33	78.95
YOD 840	160	115.89	0.93	124.33
SKY ACCN 820	180	97.45	0.98	99.26
YOD 810	190	89.84	0.91	98.50
EMP 800	200	61.61	0.89	68.87
EMP 790	210	74.57	0.89	83.47
YOD 1000	0	28.04	1.24	22.64
SKY DEC 1000	0	24.58	0.95	25.85
YOD 960	40	28.99	0.83	34.88
YOD 920	80	29.95	1.03	29.14
YOD 880	120	28.97	1.33	21.74
YOD 840	160	22.79	0.93	24.45
SKY ACCN 820	180	26.3	0.98	26.79
YOD 810	190	22.57	0.91	24.75
EMP 800	200	32.99	0.89	36.88
EMP 790	210	34.13	0.89	38.20

Modelling the trend analysis using time series analysis smoothens or reduces a lot of fluctuations in the regression equation thereby reducing a lot of errors in the model as seen in the figure 1 (thus the DE seasonalised radon concentrations were used instead of the actual radon concentration measured directly). The time series analysis reduces the error or assumes a more perfect linear equations since it reduces fluctuations. The purpose of time-series analysis is to predict or forecast future values of the variable from past observations.

Table 4: DE seasonalised radon concentration at various distances.

De seasonalized Radon Conc Y	18.32	32.38	180.99	78.95	34.88
	15.11	23.81	150.31	124.33	29.14
	10.10	135.54	125.30	99.26	21.74
	22.45	98.40	105.73	98.50	24.45
	27.57	116.77	73.58	68.87	26.79
	15.78	127.19	100.07	83.47	24.75
	7.03	105.83	86.32	22.64	36.88
	10.39	109.05	52.45	25.85	38.20

Table 5: Distances from reference level (Depth)

Distance below Reference level [1000-levels(m)] X	0	200	180	0	40
	0	210	190	40	80
	40	0	200	80	120
	80	0	210	120	160
	120	40	0	160	180
	160	80	0	180	190
	180	120	40	190	200
	190	160	80	200	210

The least square regression equation is modelled using the statistical package for social sciences.
The regression equations assume.

$$Y = \alpha + \beta X \quad (3)$$

Where α= constant value β= regression coefficient

Table 6: Trend Regression Coefficient

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	59.589	13.611	.073	4.378	.000
	Distance below Reference level	.044	.096		.453	.653

a. Dependent Variable: De seasonalized Radon Conc.

From table 6, the regression model is given as

$$Y = 59.6 + 0.073X \tag{4}$$

Where Y = Radon Concentration X = Depth (Distance from reference level)

The regression model in equation 4 and the regression coefficient (0.073) from table 6, assumes that for any unit increase in depth, radon concentration will increase by a factor of 0.073. However, the P value (0.653) being greater than the level of significance (0.05) indicates an insignificant relationship between indoor radon concentration and depth of the underground mine at the 5% level of significance.

Table 7: Trend Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.073[a]	.005	-.021	47.609

a. Predictors: (Constant), Distance below Reference level (Depth)

The regression coefficient (R = 0.073) as shown in table 7 shows there is a positive relationship between the depth (distance from the reference level) and radon concentration in the underground mine; thus, an increase in depth will lead to an increase in radon concentration in the underground goldmine and vice versa. Thus, elevated radon concentrations are expected at deeper levels of the underground mine.

The adjusted $R^2 = -0.021$ from table 7 shows that depth influences the elevation of radon concentration in the underground mine by 2.1% and 97.9% could be due to other factors that contributes to elevated levels of indoor radon that were not considered in the study. However, the negative adjusted R^2 and the P-value ($P>0.05$) of the regression coefficient in table 6 shows that the influence of depth in the underground mine on indoor radon concentration is negligible and statistically insignificant at the 5% level of significance.

Conclusion

The trend equation used for the forecasting and prediction of the radon concentration in the underground goldmine showed a positive relationship with depth from the reference level. Thus, elevated radon concentration is expected at deeper levels.

The weak and insignificant relationship between depth and indoor radon concentration in the underground mine which buttress the lower concentrations of indoor radon could be due to an appropriate engineering and adequate ventilation rate in the underground mine. This shows that when all ventilation measures are taken into consideration radon concentration will be insignificant and negligible irrespective of the level of depth in the underground mine.

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