Prediction of Airborne Radioactivity Levels in Mines Using Statistical Relationships and Artificial Neural Network

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Abstract: The main objective of the study is to define the optimal model for predicting the radiation levels of airborne radon and thoron in some Egyptian phosphate mines utilizing both statistical relationships and artificial neural network. Such prediction can be use to estimate the occupational radiation exposure of mine workers as well as for saving the time, effort and money. The study is carried out on two Egyptian phosphate mines. Radiation measurements of airborne radon and thoron have been conducted in the two mines. These measurements have been analyzed to predict the airborne radioactivity of radon and thoron levels in these mines. Six cases for predicting radon and thoron levels are investigated in each mine. Some of accuracy measurements are calculated to assess and compare the performance of statistical models and artificial neural network. The results show that using artificial neural network method for predicting both radon and thoron levels at half distance of the mine is better than the predicting each of radon or thoron separately. It is also found that the neural network method is much better than using statistical models for predicting the levels at the same distance. However, using statistical models for predicting radon or thoron levels at all distances of the mine is found to be better than using artificial neural network at half distance of the mine. The results indicated that by using two statistical models, it is not necessary to measure the levels of radon and thoron in the mine and it is possible to anticipate levels of radon and thoron all over the mine in accordance with distances.

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Key Words: Radon and thoron levels; Statistical models; Artificial neural network; Accuracy measurements.

1. Introduction

One of the occupational risks of mining result from the exposure of miners to airborne radioactive gases radon 222 (^{222}Rn), thoron 220 (^{220}Rn) and their short-lived decay products. The inhalation of these radionuclides constitutes the most important occupational exposure in mines, especially in uranium mines. It should be noted that radon and its daughters are also present in atmospheric and home air. Exposure of miners to high concentration of radon and radon decay products has been correlated with the induction of lung cancer in several mining groups. Miners' deaths probably attributable to the inhalation of radon and radon decay products are recorded as far back as the sixteen century(1).

Under the Egyptian program for radiation safety and control, airborne radioactivity measurements were conducted in some phosphate mines(2). It is well known that phosphate rocks contain the trace elements of uranium, thorium and their decay products in equilibrium. All technical processing leads to a high release of long and short half-life radionuclides from phosphate mining and milling.

Measurements were carried out of airborne radon (^{222}Rn) and thoron (^{220}Rn) gases from mine walls, ceilings and floors(3). Radioactivity measurements have been conducted in many underground phosphate mines in Egypt. Two Egyptian phosphate mines namely: El- Quser Yonus C mine and West Yonus mine are investigated. The research is based on distance as well as radon and thoron measurements for predicting their levels in the two investigated mines. Also Performance comparison of different statistical relationships and artificial neural network is made for predicting radon(*Rn*) and thoron(*Th*) levels in each mine.

Currently there are many methods available for forecasting: classification and regression tree, neural network, Bayesian prediction and time series(4). Artificial Neural Networks (ANN) are in fact the sets of mathematical models, which in their architecture, attempt to simulate the biological structure of the human brain and nervous system(5, 6).

This paper primarily focuses on radon and thoron forecasting based on Feed-Forward Backpropagation Neural Network (FFBNN) and the statistical relationships.

2. Methodology

In this study, a Feed-Forward Backpropagation Neural Network (FFBNN) have been developed. Backpropagation, or propagation of error, is a common method of teaching aritificial neural network how to perform a given task. It is used in layered feed forward ANN. This means that the artificial neurons are organized in layers, and send their signals forward, then the errors are propagated backwards as shown in Figure 1. The backpropagation algorithm uses supervised learning, which means that we provide the algorithm with examples of the inputs and outputs through connection weights. The network compute and the error between the actual and excepted results is calculated. The backpropagation algorithm is used to reduce the error, until the ANN learns the training data [7, 8].

The network developed in the present work based on typical four layers, input layer, two hidden layers and output layer.

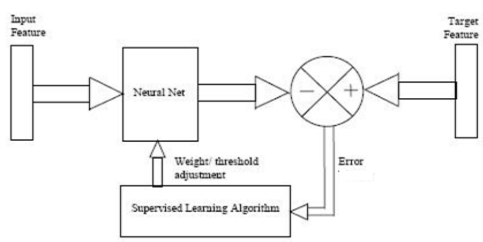

Fig. 1 Feed-Forward Backpropagation Neural Network

Different statistical relationships are used in this work. The statistical relationships represented in: the exponential, logarithm, power, linear, polynomial of second degree, polynomial of third degree and polynomial of fourth degree models.

Six cases for predicting radon and thoron levels are investigated in each mine. Some of accuracy measurements are calculated to compare the performance of statistical models and artificial neural network in each case. These accuracy measurements are calculated to assess the results between actual and predicted data as well as to reveal the most optimal model which can be use for predicting radon and thoron levels. The accuracy measurements include, the root mean square error (RMSE)[9], relative root mean square error (RRMSE)[10] and the coefficient of determination (R^2)[11]. These accuracy measurements are computed as follows:

$$RMSE=\sqrt{\frac{\sum_{i=1}^{n}\left(Y_i-\hat{Y}_i\right)^2}{n}}\ ,\ RRMSE=\sqrt{\frac{1}{n}\sum\left(\frac{Y_i-\hat{Y}_i}{Y_i}\right)^2}\ ,\ R^2=1-\frac{\sum_{i=1}^{n}\left(Y_i-\hat{Y}_i\right)^2}{\sum_{i=1}^{n}\left(Y_i-\overline{Y}_i\right)^2}$$

where, Y_i is the actual values of radon and thoron levels, $\hat{Y}_i$ is the predicted values of radon and thoron levels, $\overline{Y}$ is the mean value of radon and thoron levels and n is the total number of samples. Evaluation of the results is based on the lowest values of RMSE and RRMSE and the highest value of R^2.

3. Results and Discussion

The sample reading of radon and thoron levels was measured at different distances from the start to the end of the mine. Five readings are measured for each distance. The average of five readings is calculated for each space. Table 1 and 2 show the distances, radon and thoron measurements in Qusser Yonus C mine and west Yonus mine, respectively.

Table 1: The radon and thoron levels in Qusser Yonus C mine

Distance*(m)*	Rn *(WL)*	Th *(WL)*
50	0.035	0.012
100	0.058	0.018
160	0.0748	0.023
220	0.099	0.027
300	0.121	0.034
360	0.155	0.039
440	0.195	0.045
480	0.227	0.052
560	0.259	0.061
600	0.292	0.068
640	0.336	0.074
680	0.437	0.083
720	0.474	0.092
770	0.534	0.0996
856	0.567	0.109
910	0.617	0.116
970	0.668	0.127
1030	0.639	0.121
1090	0.594	0.112

Table 2: The radon and thoron levels in west Yonus mine

Distance*(m)*	Rn *(WL)*	Th *(WL)*
20	0.142	0.036
45	0.146	0.042
70	0.149	0.0306
95	0.151	0.046
120	0.156	0.045
145	0.163	0.049
170	0.171	0.047
190	0.178	0.06
215	0.19	0.069
235	0.217	0.078
260	0.266	0.0889
285	0.293	0.099
300	0.337	0.108
325	0.342	0.116
350	0.366	0.126
375	0.391	0.136
400	0.405	0.139

Comparison between artificial neural network (ANN) and statistical relationships is studied. This comparison is made to choose the best method which can be use for the radon and thoron prediction. The different neural network cases have been summarized in Table 3. Table 3 illustrates the number of neurons in hidden layer for the two mines and the number of hidden neurons during the prediction stage change until the minimum prediction error is reached. The Table shows the network model structures for Qusser Yonus C mine and west Yonus mine.

Table 3: Network model structures for Qusser Yonus C mine and west Yonus mine

Network cases	Number of input neurons		Input neurons details	Number of hidden layers	Output neurons details	Number of neurons in hidden layers	
	Qusser mine	west mine				Qusser mine	west mine
Case 1	9	8	Radon	2	Thoron	6-3	8-2
Case 2	9	8	Thoron	2	Radon	8-5	12-9
Case 3	9	8	Distance	2	Radon	5-4	10-7
Case 4	9	8	Distance	2	Thoron	8-2	8-3
Case 5	9	8	Distance	2	Radon and Thoron	15-10	15-8

In Qusser Yonus C mine; five statistical models are compared (the power, linear, polynomial of 2nd degree, polynomial of 3rd degree and polynomial of 4th degree models) to select the best statistical relationship for prediction. The exponential and logarithm relationships are ruled out because their results are less accurate than other models.

In west Yonus mine; five statistical relationships are compared (the logarithm or the exponential, linear, polynomial of 2nd degree, polynomial of 3rd degree and polynomial of 4th degree models). The power relationship is ruled out because its' results is less accurate than other models.

In this paper six cases for predicting radon and thoron levels in the two mines are investigated.

First case: prediction of thoron levels as a function of radon measurements

In the statistical study, the first case is based on measuring the levels of radon gas at different distances in the entire mine to predict the thoron gas levels as a function of radon measurements. This case is based on plotting the relationship between radon gas measurements (as independent variable) and thoron gas measurements (as dependent variable) to produce the thoron prediction equations. Equations (1-5) are the comparing models for thoron prediction in Qusser Yonus C mine.

$$Th = 0.1691(Rn)^{0.783} \quad (1)$$
$$Th = 0.1719(Rn) + 0.0113 \quad (2)$$
$$Th = -0.051(Rn)^2 + 0.2078(Rn) + 0.0074 \quad (3)$$
$$Th = 0.3345(Rn)^3 - 0.3967(Rn)^2 + 0.3035(Rn) + 0.0015 \quad (4)$$
$$Th = 0.539(Rn)^4 - 0.4259(Rn)^3 - 0.0472(Rn)^2 + 0.2463(Rn) + 0.0039 \quad (5)$$

Equations (6-10) are the comparing models for thoron prediction in west Yonus mine.

$$Th = 0.0938Ln(Rn) + 0.2185 \quad (6)$$
$$Th = 0.38(Rn) - 0.0134 \quad (7)$$
$$Th= -0.3654(Rn)^2 + 0.5732(Rn) - 0.0356 \quad (8)$$
$$Th = 7.4843(Rn)^3 - 6.4683(Rn)^2 + 2.1355(Rn) - 0.1594 \quad (9)$$
$$Th = -26.382(Rn)^4 + 36.073(Rn)^3 - 17.608(Rn)^2 + 3.9768(Rn) - 0.2682 \quad (10)$$

In the artificial neural network (ANN) study, the first case is based on the input data. The input data is the levels of radon gas measurements at different distances in the entire mine as well as the levels of thoron gas measurements at half distance of the mine (from distance 50*m* to 600*m* in Qusser Yonus C mine and from 20*m* to 215*m* in west Yonus mine). The output data is the prediction of thoron levels from distance 640*m* to 1090*m* in Qusser Yonus C mine and from 235*m* to 400*m* in west Yonus mine.

Table 4 shows the results of RMSE, RRMSE and R^2 for predicting thoron levels between the statistical models (from distance 50*m* to 1090*m*) and ANN method (from distance 640*m* to 1090*m*) in Qusser Yonus C mine. Tables 5 shows the results of RMSE, RRMSE and R^2 for predicting thoron levels between the statistical models (from distance 20*m* to 400*m*) and ANN method (from distance 235*m* to 400*m*) in west Yonus mine.

Table 4: The results of accuracy measurements in Qusser Yonus C mine

Model	Power	Linear	Poly. 2^{nd} degree	Poly. 3^{rd} degree	Poly. 4^{th} degree	ANN
RMSE	0.00227	0.00301	0.00251	0.00173	0.00166	0.00935
RRMSE	0.03196	0.11772	0.062231	0.031027	0.030194	0.1159
R^2	0.9978	0.9934	0.9954	0.9978	0.998	0.906

Table 5: The results of accuracy measurements in west Yonus mine

Model	Logarithm	Linear	Poly. 2^{nd} degree	Poly. 3^{rd} degree	Poly. 4^{th} degree	ANN
RMSE	0.0049	0.0053	0.0049	0.0039	0.0039	0.0094
RRMSE	0.09614	0.12042	0.10625	0.09332	0.09418	0.1021
R^2	0.9815	0.9784	0.9814	0.988	0.9884	0.985

It is clear from the results of Tables 4 and 5 that using the artificial neural network method for thoron prediction is lacking in the precision if compared with some of the statistical models. So the artificial neural network method is not recommended for use in this case.

In Qusser Yonus C mine; it is obvious from Table 4 that the polynomial of 4^{th} degree model is the best model according to accuracy measurements. The polynomial of 4^{th} degree model has the highest value of R^2 and the lowest values of RMSE and RRMSE. This model is slightly accurate than the polynomial of 3^{rd} degree and the power models, respectively. Consequently, equation 5of the 4^{th} degree polynomial model will be used for thoron prediction.

In west Yonus mine; the polynomial of 4^{th} degree model (Table 5) is slightly accurate than the polynomial of 3^{rd} degree model. Even though the value of RMSE in the two models are equal. However, the values of RRMSE and R^2 of the polynomial of 4^{th} degree model are slightly higher than the values of those of the 3^{rd} degree polynomial model. Consequently, equation 10 of the 4^{th} degree polynomial model will be used for thoron prediction.

Figures 2 and 3 show the statistical relationship between the radon levels and the actual and predicting thoron levels using polynomial 4^{th} degree model in Qusser Yonus C mine and west Yonus mine, respectively. Figures 4 and 5 show the relationship between the radon levels and the actual and predicting thoron levels using artificial neural network in Qusser Yonus C mine and west Yonus mine, respectively.

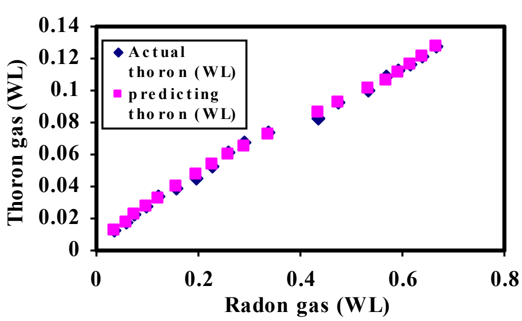

Fig. 2 the relationships between the radon gas and thoron gas in the Qusser Yonus C mine using polynomial 4th dgree model

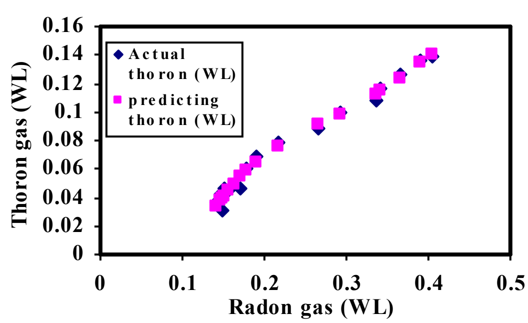

Fig. 3 the relationships between the radon gas and thoron gas in the west Yonus mine using polynomial 4^{th} dgree model

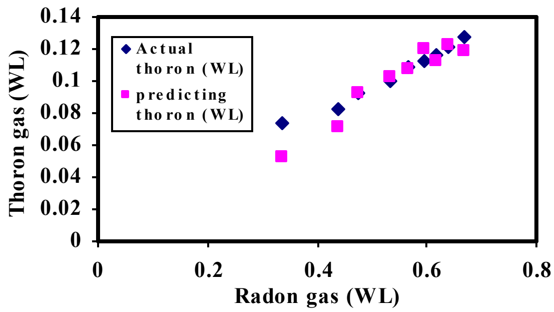

Fig. 4 the relationships between the radon gas and thoron gas in the Qusser Yonus C mine using artificial neural network

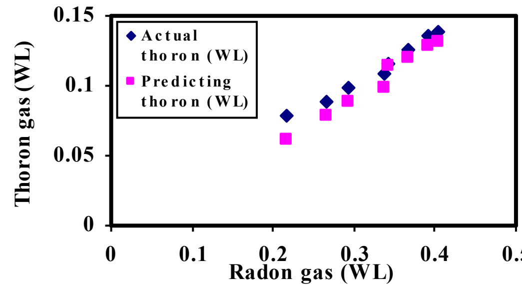

Fig. 5 the relationships between the radon gas and thoron gas in the west Yonus mine using artificial neural network

Second case: prediction of radon levels as a function of thoron measurements

The prediction of radon levels as a function of thoron measurements is carried out in a similar manner as in case 1. Equations (11-15) are the comparing models for radon prediction in Qusser Yonus C mine.

$$Rn = 9.6023(Th)^{1.2744} \tag{11}$$

$$Rn = 5.7776(Th) - 0.0633 \tag{12}$$

$$Rn = 9.1513(Th)^2 + 4.4986(Th) - 0.0312 \tag{13}$$

$$Rn = -269.67(Th)^3 + 65.097(Th)^2 + 1.2299(Th) + 0.017 \tag{14}$$

$$Rn = -4258.7(Th)^4 + 911.87(Th)^3 - 44.561(Th)^2 + 5.0741(Th) - 0.023 \tag{15}$$

Equations (16-20) are the comparing models for radon prediction in west Yonus mine.

$$Rn = 0.0988e^{10.469(Th)} \tag{16}$$

$$Rn = 2.5745(Th) + 0.0398 \tag{17}$$

$$Rn = 8.5375(Th)^2 + 1.1327(Th) + 0.0892 \tag{18}$$

$$Rn = -302.37(Th)^3 + 86.146(Th)^2 - 4.8872(Th) + 0.2264 \tag{19}$$

$$Rn = -738.4(Th)^4 - 54.229(Th)^3 + 57.024(Th)^2 - 3.4907(Th) + 0.2034 \tag{20}$$

In the artificial neural network (ANN) study, The input data is the levels of thoron gas measurements at different distances in the entire mines as well as the levels of radon gas measurements at half distance of the mines. The output data is the prediction of radon levels.

Tables 6 and 7 show the results of RMSE, RRMSE and R^2 between the statistical models and ANN for predicting radon levels in Qusser Yonus C mine and west Yonus mine, respectively.

Table 6: The results of accuracy measurements in Qusser Yonus C mine

Model	Power	Linear	Poly. 2^{nd} degree	Poly. 3^{rd} degree	Poly. 4^{th} degree	ANN
RMSE	0.014	0.0175	0.0144	0.0115	0.0106	0.0471
RRMSE	0.041	0.21014	0.0861	0.0556	0.0414	0.1193
R^2	0.9978	0.9934	0.9955	0.9972	0.9976	0.965

Table 7: The results of accuracy measurements in west Yonus mine

Model	Exponential	Linear	Poly. 2^{nd} degree	Poly. 3^{rd} degree	Poly. 4^{th} degree	ANN
RMSE	0.01304	0.0137	0.0111	0.00718	0.00716	0.0194
RRMSE	0.051	0.0757	0.0519	0.0345	0.034	0.0666
R^2	0.9815	0.9784	0.986	0.9941	0.9941	0.9771

It is evident from the results of Tables 6 and 7 that using the artificial neural network method for radon prediction is lacking in the precision if compared with some of the statistical models. So the artificial neural network method is not recommended for use in this case.

In Qusser Yonus C mine; the polynomial of 4^{th} degree model (Table 6) is slightly accurate than the power model. Even though the two models are extremely have the same values of R^2 and RRMSE. However, the polynomial of 4^{th} degree model has the slight lowest value of RMSE. Consequently, the polynomial of 4th degree model will be used as a prediction model. The equation of the 4th degree polynomial model used for radon prediction is eq. 15.

In west Yonus mine; the polynomial of 4th degree model and polynomial of 3rd degree model (Table 7) are the best relationships according to the accuracy measurements. The accuracy measurements of the polynomial of 4th degree model have a very slight difference than the accuracy measurements of the polynomial of 3rd degree model. The values of R^2 are equal in the two models but the difference between the values of RMSE and RRMSE of the both models is possible overlooked. Consequently, the polynomial of 3rd degree model will be used for radon prediction. The equation of the 3rd degree polynomial model used for radon prediction is the eq. 19.

Figures 6 and 7 show the statistical relationship between the thoron levels and the actual and predicting radon levels using 4th and 3rd degree polynomial models in Qusser Yonus C mine and west Yonus mine, respectively. Figures 8 and 9 show the relationship between radon levels and the actual and predicting thoron levels using artificial neural network in Qusser Yonus C mine and west Yonus mine, respectively.

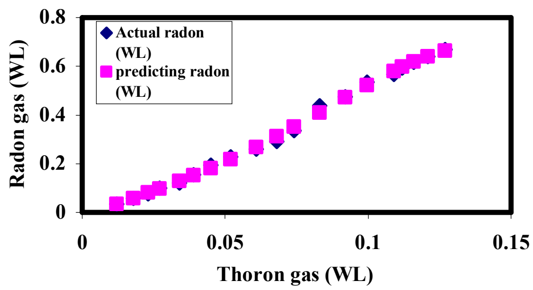

Fig. 6 the relationships between the thoron gas and radon gas in the Qusser Yonus C mine using polynomial 4th dgree model

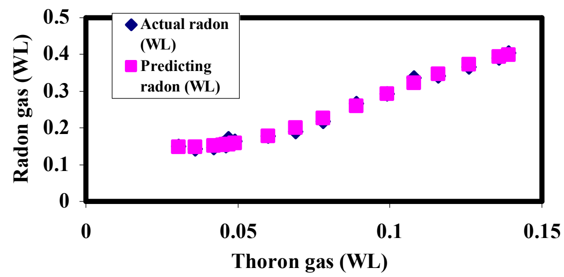

Fig. 7 the relationships between the thoron gas and radon gas in the west Yonus mine using polynomial 3rd dgree model

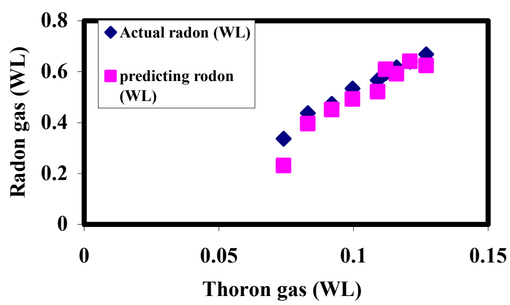

Fig. 8 the relationships between the thoron gas and radon gas in the Qusser Yonus C mine using artificial neural network

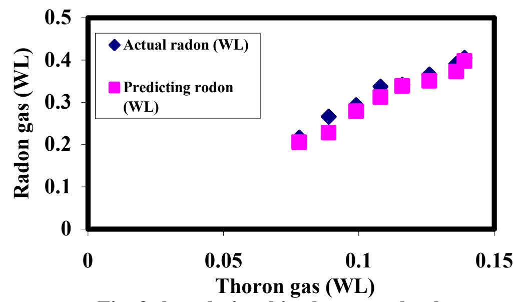

Fig. 9 the relationships between the thorongas and radon gas in the west Yonus mine using artificial neural network

Comparison between case (1) and case (2) results,

In Qusser Yonus C mine; the 4th degree polynomial model (eq. 5) that is used for thoron prediction (case 1) is better than the polynomial of 4th degree model (eq. 15) that is used for radon prediction (case 2). Because the results of the 4th degree polynomial model (eq. 5) have the lowest values of RMSE and RRMSE and highest value of R^2. Consequently, it is preferred to apply the first case in Qusser Yonus C mine for thoron prediction.

In west Yonus mine; the 3rd degree polynomial model (eq. 19) that is used for radon prediction (case 2) is better than the polynomial of 4th degree model (eq. 10) that is used for thoron prediction (case 1). Because the results of the 3rd degree polynomial model (eq. 19) have the lowest values of RRMSE and R^2. Consequently, it is preferred to apply the second case in west Yonus mine for radon prediction. It is clear from the results of accuracy measurements in first and second cases that, the artificial neural network is the worst technique for prediction. So the method of prediction using ANN in cases 1 and 2 is excluded.

Third case: prediction of radon levels as a function of distance

In the statistical study, the third case is based on measuring radon gas levels at half distance of the mine to predict the rest of radon levels as a function of distances in the entire mine. This case is based on plotting the relationship between the distances (as independent variable) and radon gas measurements (as dependent variable) to produce the radon prediction equations. The relationship is plotted from distance 50*m* to 600*m* in Qusser Yonus C mine and from distance 20*m* to 215*m* in west Yonus mine. Equations (21-25) are the comparing models for radon prediction in Qusser Yonus C mine.

$$Rn = 0.0011(d)^{0.8478} \quad (21)$$
$$Rn = 0.0005(d) + 0.0022 \quad (22)$$
$$Rn = 3E\text{-}07(d)^2 + 0.0002(d) + 0.0261 \quad (23)$$
$$Rn = 1E\text{-}10(d)^3 + 2E\text{-}07(d)^2 + 0.0003(d) + 0.0241 \quad (24)$$
$$Rn = -4E\text{-}12(d)^4 + 6E\text{-}09(d)^3 - 2E\text{-}06(d)^2 + 0.0006(d) + 0.0087 \quad (25)$$

Equations (26-29) are the comparing models for radon prediction in west Yonus mine.

$$Rn = 0.1349e^{0.0014(d)} \quad (26)$$
$$Rn = 0.0002(d) + 0.1329 \quad (27)$$
$$Rn = 1E\text{-}06(d)^2 - 2E\text{-}05(d) + 0.1434 \quad (28)$$
$$Rn = 4E\text{-}09(d)^3 - 4E\text{-}07(d)^2 + 0.0001(d) + 0.1401 \quad (29)$$

In west Yonus mine, the polynomial of 4th degree model is ruled out because its' prediction results do not represent the relationship between the distances and the radon measurements.

In the artificial neural network study, the third case is based on the input data, The input data is the different distances in the entire mine as well as the levels of radon gas measurements at half distance of the mine (from distance 50*m* to 600*m* in Qusser Yonus C mine and from 20*m* to 215*m* in west Yonus mine). The output data is the prediction of radon levels from distance 640*m* to 1090*m* in Qusser Yonus C mine and from 235*m* to 400*m* in west Yonus mine.

In this case, two types of radon prediction are investigated:

* The prediction of radon levels from distance 640*m* to 1090*m* in Qusser Yonus C mine and from distance 235*m* to 400*m* in west Yonus mine. Comparison between statistical models and ANN is made according to RMSE, RRMSE and R^2.
* The prediction of radon levels from distance 50*m* to 1090*m* in Qusser Yonus C mine and from distance 20*m* to 400*m* in west Yonus mine. Comparison between statistical models is made according to RMSE, RRMSE and R^2.

Tables 8 and 9 show the results of RMSE, RRMSE and R^2 of the statistical models and the ANN for predicting radon levels in Qusser Yonus C mine (from dist. 640*m* to 1090*m*) and west Yonus mine (from dist. 235*m* to 400*m*), respectively. Tables 10 and 11 show the results of RMSE, RRMSE and R^2 of the statistical models for predicting radon levels in Qusser Yonus C mine (from dist. 50*m* to 1090*m*) and west Yonus mine (from dist. 20*m* to 400*m*), respectively.

Table 8: The results of accuracy measurements in Qusser Yonus C mine from dist. 640-1090

Model	Power	Linear	Poly. 2nd degree	Poly. 3rd degree	Poly. 4th degree	ANN
RMSE	0.2149	0.1235	0.133	0.083	0.1045	0.0462
RRMSE	0.378	0.2163	0.248	0.154	0.2190	0.0863
R^2	0.7754	0.767	0.726	0.715	0.1962	0.9658

Table 9: The results of accuracy measurements in west Yonus mine from dist. 235-400

Model	Exponential	Linear	Poly. 2nd degree	Poly. 3rd degree	ANN
RMSE	0.125	0.140	0.0923	0.063	0.0197
RRMSE	0.352	0.395	0.2649	0.192	0.0644
R^2	0.937	0.951	0.9171	0.877	0.978

Table 10: The results of accuracy measurements in Qusser Yonus C mine from dist. 50-1090

Model	Power	Linear	Poly. 2nd degree	Poly. 3rd degree	Poly. 4th degree
RMSE	0.1485	0.0861	0.0927	0.0575	0.0851
RRMSE	0.2697	0.1834	0.1918	0.1159	0.2341
R^2	0.9784	0.9855	0.9968	0.9968	0.9976

Table 11: The results of accuracy measurements in west Yonus mine from dist. 20-400

Model	Exponential	Linear	Poly. 2nd degree	Poly. 3rd degree
RMSE	0.0857	0.0962	0.0633	0.0432
RRMSE	0.242	0.272	0.182	0.133
R^2	0.9538	0.9368	0.996	0.9986

It is obvious from Tables 8 and 9 that the ANN is the best method for radon prediction according to the lowest values of RMSE and RRMSE as well as the highest value of R^2. In this type of prediction, the artificial neural network method will be used as a prediction method.

From Tables 10 and 11, the polynomial of 3rd degree models are the best models for predicting radon levels in Qusser Yonus C mine and west Yonus mine. The polynomial of 3rd degree models have the lowest values of RMSE and RRMSE as well as the highest value of R^2. The equations of the 3rd degree polynomial model used for predicting radon levels in the entire mines are eq. 24 and eq. 29, respectively.

Figures 10 and 11 show the statistical relationships between the distances and the actual and predicting radon levels using polynomial of 3rd degree model in Qusser Yonus C mine and west Yonus mine, respectively. Figures 12 and 13 show the relationship between the distances and the actual and predicting radon levels using artificial neural network in Qusser Yonus C mine and west Yonus mine, respectively.

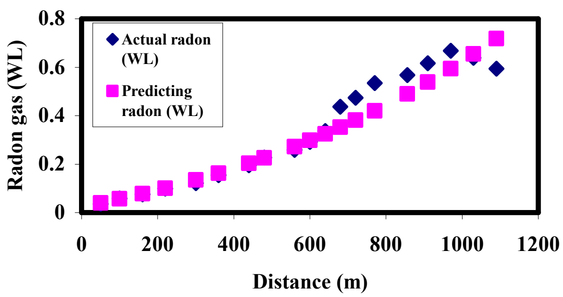

Fig. 10 the relationships between the distance and radon gas in the Qusser Yonus C mine using polynomial 3rd dgree model

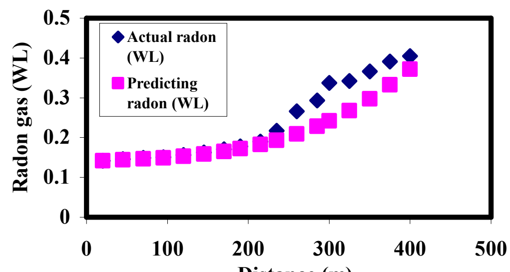

Fig. 11 the relationships between the distance and radon gas in the west Yonus mine using polynomial 3rd dgree model

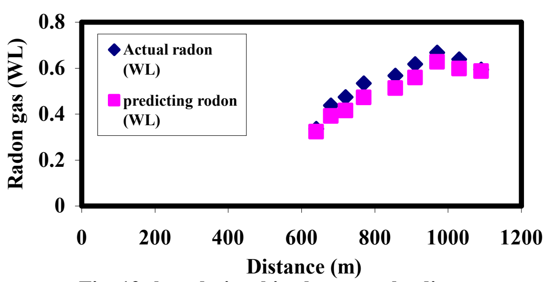

Fig. 12 the relationships between the distances and the radon measurements in the Qusser Yonus C mine using artificial neural network

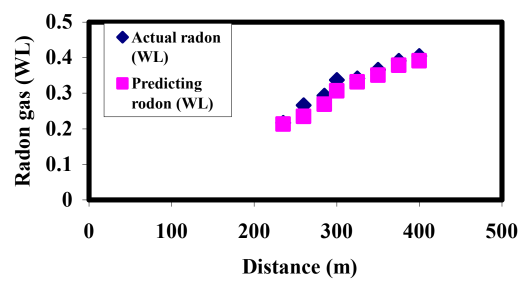

Fig. 13 the relationships between the distances and the radon measurements in the west Yonus mine using artificial neural network

Fourth case: prediction of thoron levels as a function of distance

The prediction of thoron levels as a function of distance is carried out in a similar manner as in case 3. Equations (30-34) are the comparing models for thoron prediction in Qusser Yonus C mine.

$$Th = 0.0008(d)^{0.6765} \quad (30)$$
$$Th = 1E\text{-}04(d) + 0.0066 \quad (31)$$
$$Th = 6E\text{-}08(d)^2 + 6E\text{-}05(d) + 0.0108 \quad (32)$$
$$Th = 3E\text{-}10(d)^3 - 2E\text{-}07(d)^2 + 0.0001(d) + 0.0064 \quad (33)$$
$$Th = -2E\text{-}13(d)^4 + 6E\text{-}10(d)^3 - 3E\text{-}07(d)^2 + 0.0001(d) + 0.0055 \quad (34)$$

Equations (35-38) are the comparing models for thoron prediction in west Yonus mine.

$$Th = 0.0317e^{0.0031(d)} \quad (35)$$
$$Th = 0.0002(d) + 0.0293 \quad (36)$$
$$Th = 1E\text{-}06(d)^2 - 8E\text{-}05(d) + 0.0389 \quad (37)$$
$$Th = 6E\text{-}09(d)^3 - 1E\text{-}06(d)^2 + 0.0001(d) + 0.0342 \quad (38)$$

In west Yonus mine, the polynomial 4th degree model is ruled out because its' results of prediction do not represent the relationship between the distances and the thoron measurements.

In the artificial neural network study, the input data is the different distances in the entire mines as well as the levels of radon gas measurements at half distance of the mines. The output data is the prediction of radon levels.

Tables 12 and 13 show the results of RMSE, RRMSE and R^2 of the statistical models and ANN for predicting the thoron levels in Qusser Yonus C mine (from dist. 640*m* to 1090*m*) and west Yonus mine (from dist. 235*m* to 400*m*), respectively.

Tables 14 and 15 show the results of RMSE, RRMSE and R^2 of the statistical models for predicting thoron levels in Qusser Yonus C mine (from dist. 50*m* to 1090*m*) and west Yonus mine (from dist. 20*m* to 400*m*), respectively.

Table 12: The results of accuracy measurements in Qusser Yonus C mine from dist. 640-1090

Model	Power	Linear	Poly. 2nd degree	Poly. 3rd degree	Poly. 4th degree	ANN
RMSE	0.0288	0.0143	0.0134	0.0675	0.0642	0.0114
RRMSE	0.261	0.130	0.120	0.585	0.555	0.131
R^2	0.804	0.7877	0.7536	0.65335	0.7055	0.8885

Table 13: The results of accuracy measurements in west Yonus mine from dist. 235-400

Model	Exponential	Linear	Poly.2nd degree	Poly. 3rd degree	ANN
RMSE	0.0267	0.0213	0.0115	0.0773	0.0065
RRMSE	0.1633	0.1461	0.1071	0.2780	0.0573
R^2	0.968	0.9873	0.9642	0.9276	0.9825

Table 14: The results of accuracy measurements in Qusser Yonus C mine from dist. 50-1090

Model	Power	Linear	Poly. 2nd degree	Poly. 3rd degree	Poly. 4th degree
RMSE	0.01999	0.00999	0.0093	0.0467	0.0446
RRMSE	0.1906	0.1017	0.0945	0.4227	0.4216
R^2	0.9772	0.9866	0.9949	0.9986	0.9986

Table 15: The results of accuracy measurements in west Yonus mine from dist. 20-400

Model	Exponential	Linear	Poly. 2nd degree	Poly. 3rd degree
RMSE	0.0177	0.0151	0.0080	0.0502
RRMSE	0.1821	0.1925	0.1012	0.4059
R^2	0.9772	0.9866	0.9949	0.9986

It is obvious from Tables 12 and 13 that the ANN is the best method according to the lowest values of RMSE and RRMSE as well as the highest value of R^2. In this type of prediction, the artificial neural network method will be used as a prediction technique.

From Tables 14 and 15, the polynomial of 2nd degree models are the best models for predicting thoron levels in Qusser Yonus C mine and west Yonus mine. Even though the value of R^2 of the polynomial of 2nd degree models is slightly lower than the value of R^2 of the other models. However, the two models have the lowest values of RMSE and RRMSE. The equations of the 2nd degree polynomial model used for predicting thoron levels in entire Qusser Yonus C and west Yonus mines are eq. 32 and eq. 37, respectively.

Figures 14 and 15 show the statistical relationships between the distances and the actual and predicting thoron levels using polynomial of 2nd degree model in Qusser Yonus C mine and west Yonus mine, respectively. Figures 16 and 17 show the relationship between the distances and the actual and predicting thoron levels using artificial neural network in Qusser Yonus C mine and west Yonus mine, respectively.

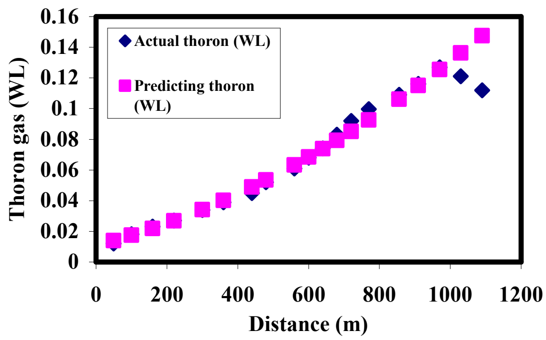

Fig. 14 the relationships between the distance and thoron level in the Qusser Yonus C mine using polynomial 2nd dgree model

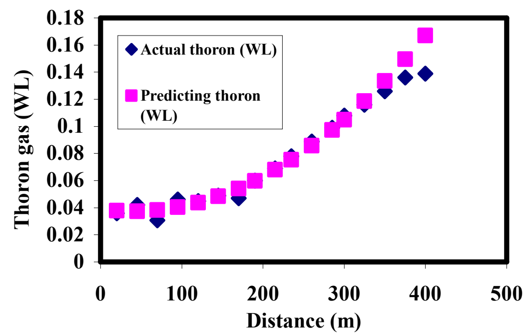

Fig. 15 the relationships between the distance and thoron levels in the west Yonus mine using polynomial 2nd dgree model

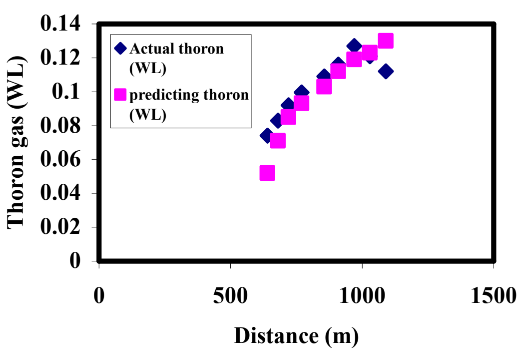

Fig. 16 the relationships between the distances and the thoron measurements in the Qusser Yonus C mine using artificial neural network

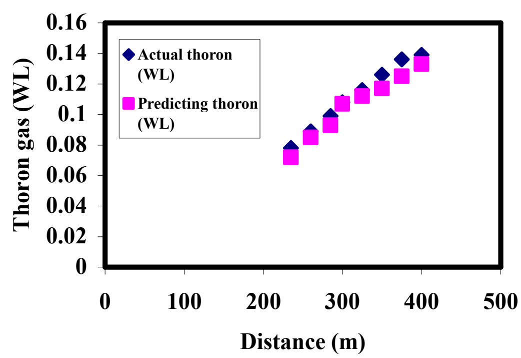

Fig. 17 the relationships between the distances and the thoron measurements in the west Yonus mine using artificial neural network

Comparison between case (3) and case (4) results,

According to the lowest values of RMSE and RRMSE as well as the highest value of R^2, using the ANN method for predicting radon levels (case 3) or thoron levels (case 4) are much better than using statistical models for predicting radon levels (case 3) or thoron levels (case 4) at the same distances of the two mines. Moreover, using some statistical models for predicting radon levels (case 3) or thoron levels (case 4) at all distances of the two mines is better than using ANN method for predicting radon levels (case 3) or thoron levels (case 4) at half distance of the two mines. Applying the polynomial of 2nd degree models (eq. 32 and eq. 37) that are used for thoron prediction in the two investigated mines (case 4) are better than applying the 3rd degree polynomial models (eq. 24 and eq. 29) that are used for radon prediction (case 3). Because the results of accuracy measurements of the polynomial of 2nd degree models have the lowest values of RMSE and RRMSE. Consequently, it is preferred to apply the fourth case in Qusser Yonus C and west Yonus mines for thoron prediction.

Fifth case: prediction of radon and thoron levels using artificial neural network

The fifth case is based on the input data. The input data is the different distances in entire the mine and the levels of radon and thoron gas measurements in half distance of the mine (from distance 50*m* to 600*m* in Qusser Yonus C mine and from 20*m* to 215*m* in west Yonus mine). The output data is the prediction of radon and thoron levels from distance 640 *m* to 1090*m* in Qusser Yonus C mine and from 235*m* to 400*m* in west Yonus mine.

Tables 16 shows the results of RMSE, RRMSE and R^2 of radon and thoron prediction in Qusser Yonus C mine and west Yonus mine, respectively.

Table 16: The results of accuracy measurements of radon and thoron prediction in Qusser Yonus C mine and west Yonus mine using artificial neural network

Mine	Qusser Yonus C mine		West Yonus mine	
Accuracy measurements	Radon prediction	Thoron prediction	Radon prediction	Thoron prediction
RMSE	0.0057	0.0022	0.0055	0.0029
RRMSE	0.0116	0.0232	0.0172	0.0246
R^2	0.998	0.991	0.999	0.995

It is obvious from the results that the method of predicting both radon and thoron levels (Table 16) is better than the method of predicting radon or thoron separately (at the same distances in third and fourth cases). The results of RMSE, RRMSE and R^2 in Table 16 are more accurate than the results of RMSE, RRMSE and R^2 in Tables 8,9,12 and13, respectively. Consequently, applying this case for prediction is preferred.

Figures 18 and 19 show the relationship between the distances and the actual and predicting radon and thoron levels using ANN in Qusser Yonus C mine and west Yonus mine, respectively.

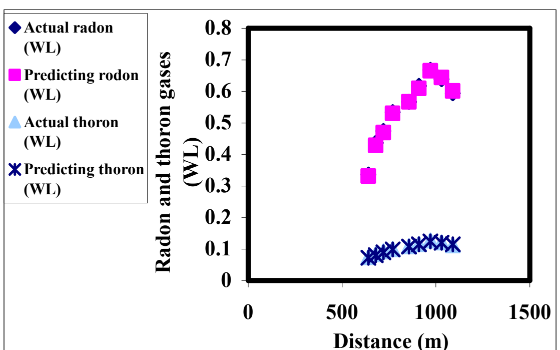

Fig. 18 the relationships between the distances and the radon and thoron measurementsin Qusser Yonus C mine using artificial neural network

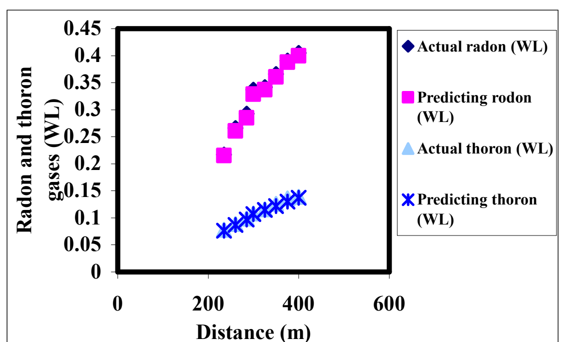

Fig. 19 the relationships between the distances and the radon and thoron measurementsin west Yonus mine using artificial neural network

Sixth case: prediction of thoron levels as a function of distance to predict radon levels as a function of predicting thoron levels using statistical models

The prediction in this case is based on the distances only (from dist. 50*m* to 1090*m* in Qusser Yonus C mine and from dist. 20*m* to 400*m* in west Yonus mine). The prediction is divided in two steps.

The first step is based on case 4 by selecting and applying the best prediction model to predict thoron levels as a function of distance in the entire mine. Case 4 is better than case 3 according to the lowest valus of RMSE and RRMSE. The prediction equation of thoron levels in Qusser Yonus C mine is eq. 32. The prediction equation of thoron levels in west Yonus mine is eq. 37. **The second step** is based on case 2 by selecting and applying the best investigated prediction model to predict radon levels as a function of thoron levels in the entire mine. This prediction is carried out after predicting thoron levels according to the first step.

In Qusser Yonus C mine; the 4th degree polynomial model (case 2) is the best prediction model to predict the radon levels in entire the mine. By substituting the predicting thoron levels (the results of eq. 32) in the 4th polynomial degree model (eq. 15), the radon levels will be predicted.

In west Yonus mine; the polynomial of 3rd degree model (case 2) is the best prediction model to predict the radon levels in entire the mine. By substituting the predicting thoron levels (the results of eq. 37) in the polynomial of 3rd degree model (eq. 19), the radon levels will be predicted. Table 17 show the results of RMSE, RRMSE and R^2 of radon and thoron prediction in Qusser Yonus C mine and west Yonus mine using statistical models.

Table 17: The results of accuracy measurements of radon and thoron prediction in Qusser Yonus C mine and west Yonus mine using statistical models

Mine	Qusser Yonus C mine		West Yonus mine	
Accuracy measurements	Thoron prediction	Radon prediction	Thoron prediction	Radon prediction
RMSE	0.0093	0.0247	0.0080	0.0109
RRMSE	0.0945	0.0766	0.1012	0.0361
R^2	0.9949	0.9811	0.9949	0.9873

Table 17 shows that the values of errors are very small and the value of coefficient of determination is high. Consequently, this case is considered the best statistical method for predicting radon and thoron levels in the two investegated mines. Moreover, it is preffered to use this case for prediction because it saves the time, effort and money as well as it is very easy method for prediction. In this case, it is not necessary to measure the levels of radon and thoron in the mines. It is possible to anticipate levels of radon and thoron all over the mine in accordance with distances. Consequently, applying this case for predicting radon and thoron levels is recommended.

Conclusion

In this study, comparison between some statistical models and artificial neural network is carried out to define the optimal model for predicting the radiation levels of airborne radon and thoron in two Egyptian phosphate mines. Six cases for predicting radon and thoron levels are investigated in Qusser Yonus C mine and west Yonus mine. RMSE, RRMSE and R^2 are calculated to assess and compare the performance of statistical models and artificial neural network. The results indicate that using artificial neural network method for predicting both radon and thoron levels at half distance of the mine is better than predicting each of radon or thoron separately. Also, using artificial neural network method for predicting both radon and thoron levels or separately at half distance of both mines is much better than using statistical models for prediction at the same distance in each mine. Moreover, using some statistical models for predicting radon or thoron levels in the mine at all distances is better than using artificial neural network method for predicting of radon or thoron levels at half distance of the mine. The results show that the statistical models are powerful tools in anticipation levels of radon and thoron all over the mine in accordance with distances.

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