Statistical Prediction Model for Terrestrial Gamma Radiation Measurements in an Area Based on Geological Formations and Soil Types

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Abstract: This study aims to produce a model for the prediction and estimation of unmeasured terrestrial gamma dose rate (TGDR) using statistical analysis based on geological formation and soil type. The measurements of TGDR were conducted in the Pahang state Malaysia, with a total of 640 measured points that covers all geological formations and soil types in the state. The measurements were taken 1 m above the soil surface using Ludlum 19 gamma ray (μR) meter. The measured gamma dose rates ranged from 26 nGy h^{-1} to 750 nGy h^{-1} with a mean value of 176 nGy h^{-1}. The data have been normalized to fit a normal distribution. Significance testing was conducted among all geological formations and soil types, using one way analysis of variance (ANOVA). The results indicated strong significant differences due to the different geological formations and soil types present in the State. Pearson Correlation was used to measure the relations between gamma dose rate based on geological formation and soil type (G_D,S_D) with the gamma dose rate based on geological formation (G_D) or gamma dose rate base on soil type (S_D). A very good correlation (88.3%) was found between G_D,S_D and G_D or G_D,S_D and S_D. A total of 85 pairs of geological formations and soil types were used to derive the statistical contribution of geological formations and soil types to gamma dose rates. The percentage contribution of the gamma dose rate from geological formation and soil type were found to be 0.580 and 0.311, respectively. The null hypotheses were accepted for 88% of examined data, therefore, the model could be used to predict gamma dose rates based on geological formation and soil type information.

Key words: Geological formation, gamma dose rate, soil type, statistical prediction model.

1. Introduction

Various measurements were made on terrestrial gamma radiation (TGR) measurements in different parts of the world, all in the view to determine the values for TGR in the environment and the corresponding heath implications to the populace.

Most of the radioactivity in the terrestrial environment, whether it is natural or man-made, binds to the components of the soil [1]. Therefore, all exposures that originate from soil are potentially important for the purpose of radiation risk assessment. Higher radioactivity in soil samples may be linked to the contribution of the parent materials that constitute the soil type [2]. For instance, soil derived from granite rocks which originates from acid intrusive geological formation will have a higher radioactivity than the soil from the other rock types. This is the reason why peat soil, which is an accumulation of partially decayed vegetation has lower radioactivity [3] and [4].

Radioactivity levels vary greatly depending on soil type and the mineral make-up. The higher concentrations of uranium, thorium and potassium are associated with soil developed from acid intrusive rocks. Most uranium is associated with the phosphate sands and clays originating from acid intrusive geological formations [5].

Soil acts as a channel for the transfer of radionuclides to plants and animals and hence, it is the basic indicator of the radiological status of the environment. Soil that has a high radiation dose levels are usually caused by the presence of some minerals such as monazite [6].High readings are also due to the contribution of radioactivity from the soil parent material [7].

Relationships between terrestrial gamma radiation dose rate, soil types and the underlying geological formation has been investigated previously [8]-[11]. Statistical evaluations of the results were carried out.

The results were however obtained after an extensive, tedious and expensive field work. The prediction model is therefore required in other to predict terrestrial gamma dose rate with a minimum field work.

In this study, a prediction model base on the geological formations and soil types was statistically evaluated using the data obtained in Pahang state Malaysia [8].

2. Materials and Methods

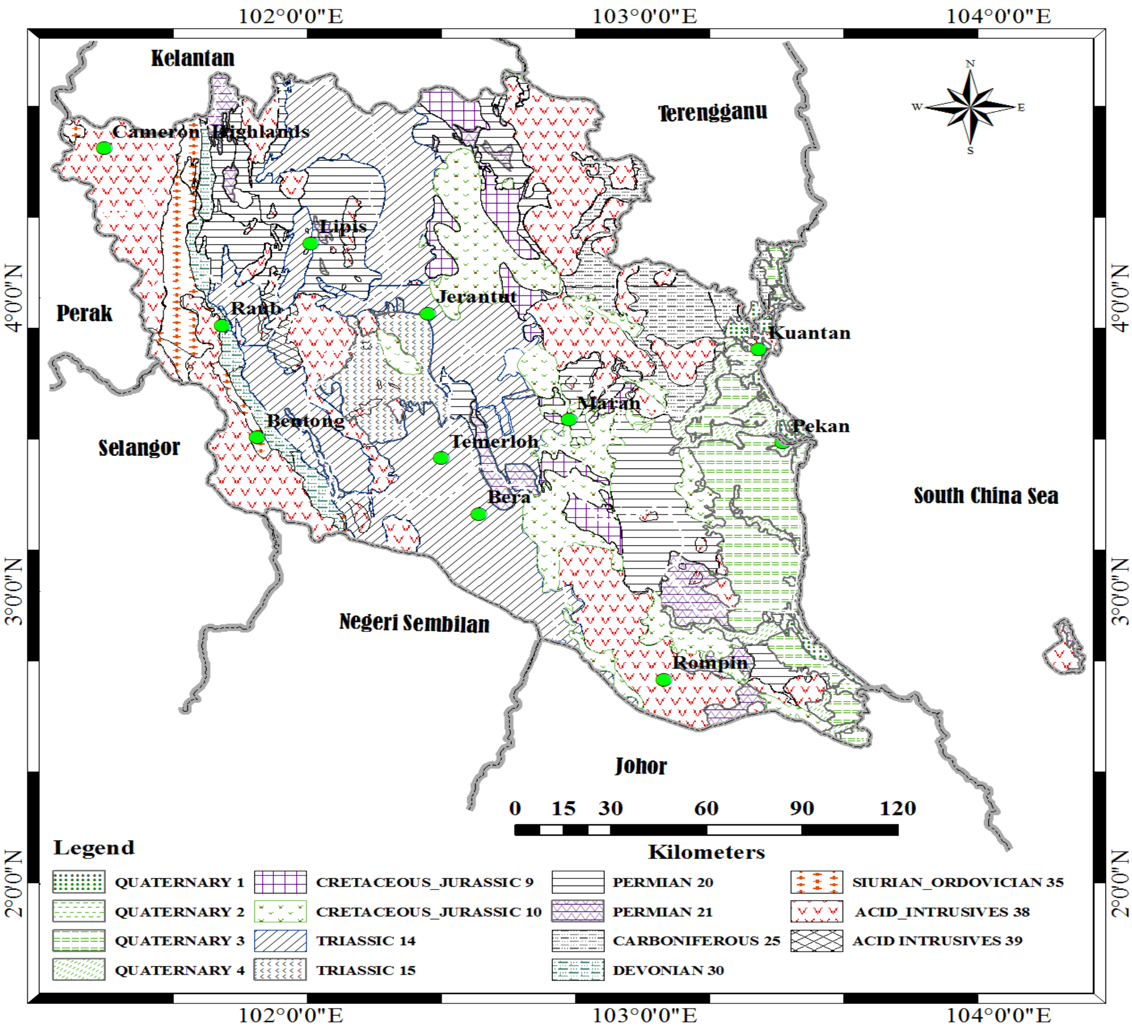

Fig. 1. Geological formations of Pahang state [13].

Terrestrial gamma dose rate (TGDR) was measured 1 m above the soil from various locations. The measurement points were chosen based on the geological formation (Fig. 1) and soil types (Table 1.) of the area. The TGDR measurements were taken using a gamma-ray detector at each point, recorded with a Global Positioning System Receiver Garmin (GPSmap 76) from the location of the latitude and longitude of each surveying point. The average value was recorded from four measurements around each point. The detector used was model 19, micro Roentgen (μR) meter, manufactured by Ludlum, USA. It uses sodium iodide (NaI) crystal doped with thallium (Tl) as an activator. The approximate linear energy of the detector falls between 0.80 MeV and 1.2 MeV, this ranges covers the majority of significant gamma-ray emissions from terrestrial sources. The detection of gamma-rays from cosmic rays is negligible due to the detector's low response to high-energy Gamma radiation [1] and [12].

Table 1. Soil types in Pahang State

S/N	Soil type	Local name	FAO / UNESCO UNIT
1	(1)	Rudua-Rusila	HumicPodzols-Dytstric Fluvisols
2	(2)	Keranji	Thionic Fluvisol
3	(8)	Beriah-lempung organan & muk	Organic Clay and Muck
4	(9)	Lempung organan and muck	Organic clay and muck
5	(10)	Tanah Gambut (Peat)	Dystric Histosols
6	(11)	Telemong Akob- Tanah Lanar Tempatan	Dystric Fluvisols - Dystric Gleysol
7	(16)	Sogomana-sitiawan-manik	Gleyic Acrisols
8	(18)	Holyrood lunas	Xanthic Ferrasols -Dystric Gleysols
9	(19)	Kelau-Kawang	Ferric Acrisols-Haplic Acrisol
10	(20)	Harimau Tampoi	Ferric Acrisols -Ferric Acrisols
11	(21)	Batu Anam-Durian	Orthic Acrisols-Ferric Acrisols
12	(22)	Batu Anam-Melaka -Tavy	OrthicAcrisols-Plinthic Ferralsols
13	(23)	Marang-Apek	Plinthic Acrisols-Plinthic Acrisols
14	(25)	Gajah Mati-Munchong-Malacca	PlinthicFerralsols-Plinthic Ferralsols- Plinthic Ferralsols
15	(26)	Durian-Malacca-Tavy	FerricAcrisols-Plinthic Ferralsols-Plinthic Ferralsols
16	(27)	Munchong-Seremban	Orthic Ferralsols
17	(28)	Munchong-Serdang	OrthicFerralsols-Ferric Acrisols
18	(29)	Bungor-Munchong	FerricAcrisols-Orthic Ferralsols
19	(30)	Serdang-Bungor-Munchong	FerricAcrisols-Ferric AcrisoIs-Orthic Ferrasols
20	(31)	Rengam-Jerangau	DystricNitosols-Orthic Ferrasols
21	(32)	Rengam-Tampin	DystricNitosols-Ferric Acrisols
22	(33)	Segamat-Katong	Rhodic Ferralsols-Xanthic ferralsols
23	(34)	Kuantan	Rhodic Nitosols
24	(35)	Prang	Rhodic Ferralsols
25	(37)	Langkawi	Ferric Acrisols-DystricNitosols
26	(38)	Durian-Munchong-Bungor	FerricAcrisols-Orthic Ferralsols- Ferric Acrisols
27	(39)	Bungor durian	Ferric Acrisol- Orthic Ferrasols
28	(41)	Jempol	Rhodic Ferralsols
29	(43)	Kuala berang-Kedah-Serdang	Latosols
30	(45)	Serdang-Kedah	Ferric Acrisols
31	(47)	Rengam-Bukit Temiang	Dystric Nitosols
32	(48)	Tanah Curam	Steep land
33	(49)	Tanah Bandar	Urban Land
34	(50)	Tanah lombong	Mined land

3. Results and Discussion

Fig. 2 shows the box plot for gamma dose rate and geological formation in the study area. The box plot shows the median values (the centre line of the box) of all the geological formations are less than 200 nGy h^{-1} except for acid intrusive (38) and (39) which has higher values. Geological formations (4), (35), (38) and (39) have almost a symmetric box indicating that their values are almost normally distributed. Geological formation (10) and (14) have both outliers (o) and extreme outliers (*) with values greater than 1.5 times and 3 times the interquatile range (length of the box) respectively. Acid intrusive formation (39) has the highest mean value and quaternary (3) geological formation has the lowest mean value of dose rate.

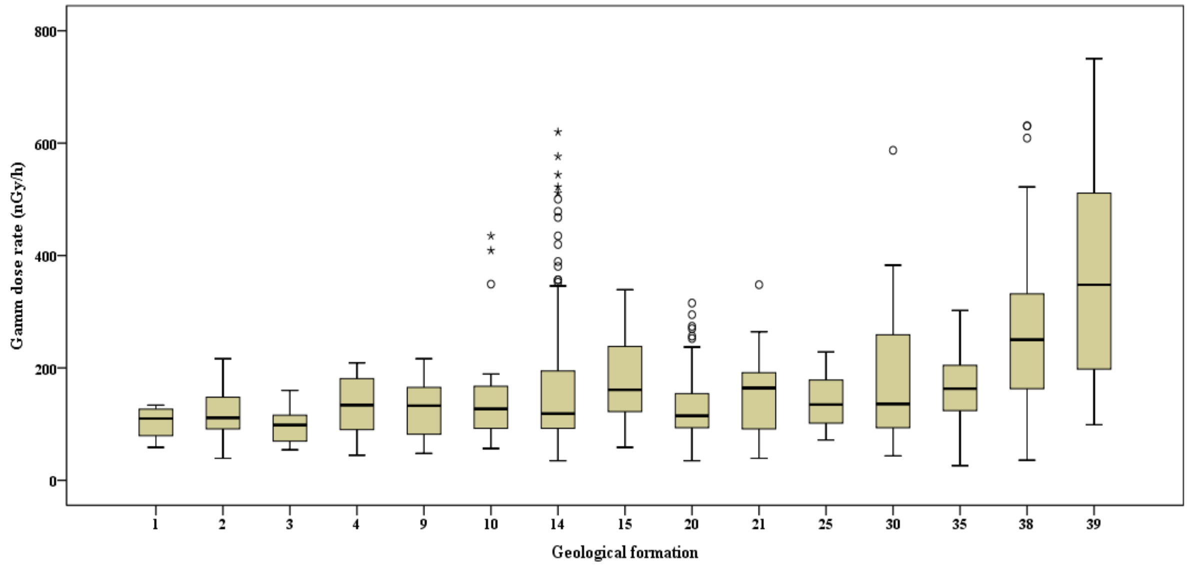

Fig. 2. Box plot for TGDR and geological formation in the study area.

Fig. 3 shows the box plot for gamma dose rate and soil types in the study area. The plot shows some outliers and extreme outliers particularly soil type (38) which has the highest number of measurement. Majority of the plots are positively skewed. This explains the positive skewness of the measured data in the study area. Soil type (48) Steep land and soil type (31) DystricNitosols-Orthic Ferrasols, has the minimum and the maximum values of the TGDR in the area as shown by the lower and upper whiskers from their respective box plots.

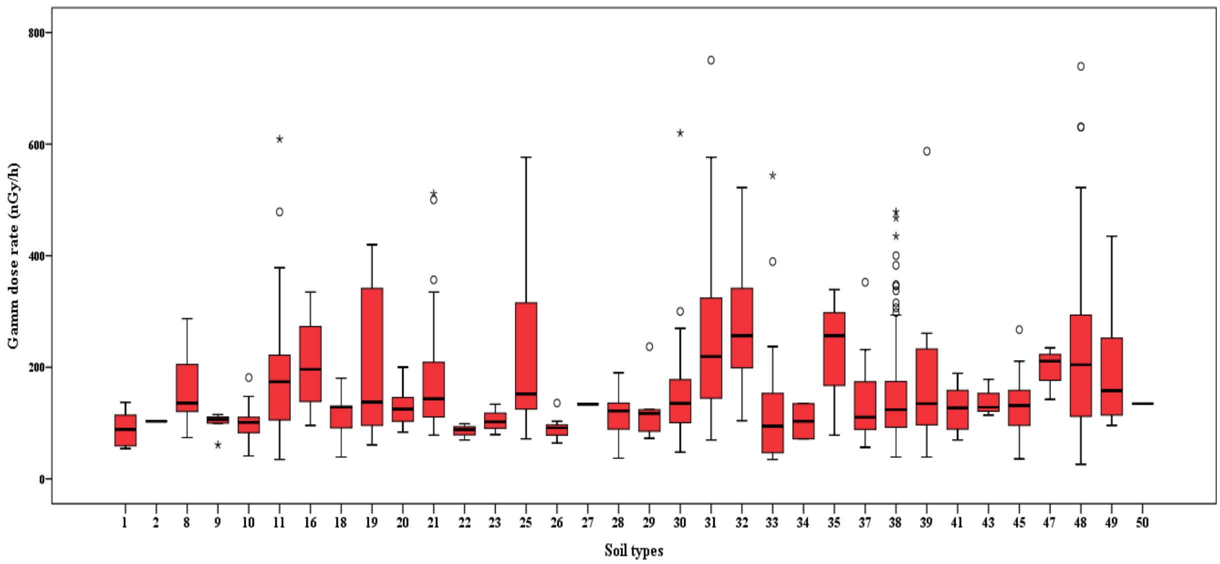

Fig. 3. Box plot for TGDR and soil type in the study area.

4. Statistical Prediction

Statistical prediction model is important in other to predict terrestrial gamma dose rate with a minimum field work. In this study the prediction was carried out base on the geological formations and soil types in the area. Multi regression analysis was performed on the measured TGDR values for the geology and soil where a linear regression equation was obtained. The result of multi-regression analysis for the prediction of terrestrial gamma radiation dose rate (TGDR) based on geological formations and soil types are given in Tables 2, 3 and 4.

Table 2. Prediction Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.883	0.779	0.778	98.919

Table 3. ANOVA Results for the Prediction Model

Model		Sum of Squares	df	Mean Square	F	Sig.(P)
1	Regression	21998381	2	10999190	1124	0.000
	Residual	6242827	638	9785		
	Total	28241208	640			

Table 4. Coefficients of the Prediction Model

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.(P)
		B	Std. Error	Beta	Tolerance	VIF
1	SOIL	0.359	0.073	0.311	4.925	0.000
	GEO	0.660	0.072	0.580	9.176	0.000

Table 2 the prediction model summary the value of the correlation coefficient *"R"* is seen to be 0.883 (88.3%) which shows that a good correlation exits between the dependent variable (TGDR) and the two independent variables (TGDR base on geological formations and soil types). Higher value of *"R"* indicates that the predicted values are more closely correlated to the dependent variable (i.e., the greater the value of *R*, the better the independent variables are at predicting the dependent variable). A value of 0.883, in this case, indicates a good level of prediction. The adjusted *R* square value of 0.778 indicates that the independent variables (soil and geology) explain 77.8% of the variability of our dependent variable (TGDR).

Table 3 the ANOVA results for the model shows that the independent variables statistically significantly predict the dependent variable with $F\,(2, 638) = 1124$, *Sig.(P)* < 0.001 that satisfied the null hypothesis (i.e., the regression model is a good fit of the data).

Table 4 the coefficient of the model shows the standardized coefficient (Beta) which gives the coefficient for the linear regression equation for the model. The general linear equation model for the prediction of TGDR base on geological formation and soil types is therefore given as;

$$Predicted\,TGDR = 0.580(G_D) + 0.311(S_D) \quad (1)$$

where G_D is TGDR on $geological\ formation\ and\ S_D\ is$ TGDR on $Soil\ type$

The predicted mean TGDR for Pahang state is found to be 157 nGy h^{-1}. This value compares well with the measured mean TGDR, which is 176 nGy h^{-1}, it is about 11% lower than the measured mean TGDR. This level of error is acceptable for environmental radiological protection purposes [14]. The highest TGDR predicted is 296 nGy h^{-1} and the highest measured TGDR due to geology and soil combination is 631 nGy h^{-1}. All are coming from acid intrusive geological formation (39). The lowest predicted TGDR is 87nGy h^{-1} while the lowest measured mean dose rate due to geology and soil is 83 nGy h^{-1}, all coming from quaternary geological formation and from the soil type (1) HumicPodzols-Dytstric Fluvisols. All values compares well to each other.

Table 5 shows, eighty five combinations of soil types and geological formations in Pahang state with the results of the hypothesis testing for the prediction model obtained.

Table 5. Combination of Geological Formations and Soil Types with Hypothesis Test

Geological formation G_i	**Soil type S_i**	**Measured $D_{G,S}$(nGy h^{1}) $G_i \cap S_i$**	**Predicated $D_{G,S}$ (nGy h^{1})**	**Mean Difference (nGy h^{1})**	**T-test**	**Sig. (P)**	**Hypothesis**
1	38	127	111	16	2.220	0.2	Accepted
2	1	103	99	4	0.174	0.8	Accepted
2	10	109	105	4	0.342	0.7	Accepted
2	11	195	130	65	3.075	0.2	Accepted
2	18	110	108	2	0.062	0.9	Accepted
3	1	83	87	-4	-0.445	0.6	Accepted
3	9	96	90	6	0.327	0.7	Accepted
3	30	137	112	25	1.096	0.4	Accepted
4	8	194	133	61	4.163	0.1	Accepted
4	11	102	137	-35	-1.205	0.3	Accepted
4	30	134	131	3	0.082	0.9	Accepted
4	49	144	141	3	0.065	0.9	Accepted
9	11	130	134	-4	-0.108	0.9	Accepted
9	28	125	111	14	0.814	0.4	Accepted
10	8	134	141	-7	-3.328	0.1	Accepted
10	11	161	146	15	0.461	0.6	Accepted
10	30	103	139	-36	-2.188	0.1	Accepted
10	38	116	137	-21	-1.003	0.3	Accepted
10	41	167	128	40	1.824	0.3	Accepted
10	48	144	162	-19	-0.418	0.6	Accepted
14	10	90	126	-36	-3.369	0.0	**Rejected**
14	11	174	151	23	2.244	0.0	**Rejected**
14	19	198	159	39	0.718	0.4	Accepted
14	20	118	135	-17	-1.560	0.2	Accepted
14	21	181	153	28	1.273	0.2	Accepted
14	22	86	119	-33	-3.903	0.0	Accepted
14	23	105	126	-21	-1.320	0.3	Accepted
14	26	91	121	-30	-5.282	0.0	**Rejected**

14	28	102	129	-26	-3.081	0.0	**Rejected**
14	29	101	131	-31	-1.313	0.4	Accepted
14	30	198	145	53	0.835	0.4	Accepted
14	31	134	179	-45	-1.630	0.2	Accepted
14	32	254	180	74	1.937	0.0	Accepted
14	33	138	139	-1	-0.017	0.9	Accepted
14	37	115	140	-25	-1.186	0.2	Accepted
14	38	163	142	20	1.284	0.2	Accepted
15	11	203	164	39	0.527	0.6	Accepted
15	21	136	165	-29	-1.504	0.3	Accepted
15	31	234	191	43	2.279	0.1	Accepted
15	38	160	155	5	0.182	0.8	Accepted
15	41	114	146	-32	-0.711	0.6	Accepted
15	45	185	150	36	1.069	0.3	Accepted
15	48	165	181	-16	-0.581	0.5	Accepted
20	11	158	137	21	0.924	0.3	Accepted
20	25	180	151	29	0.399	0.7	Accepted
20	28	131	114	17	3.831	0.1	Accepted
20	29	136	116	20	0.562	0.6	Accepted
20	30	97	130	-33	-1.977	0.1	Accepted
20	31	197	164	33	0.946	0.5	Accepted
20	38	114	127	-13	-1.501	0.1	Accepted
20	41	99	119	-20	-2.012	0.2	Accepted
20	48	84	153	-70	-5.269	0.0	**Rejected**
20	49	131	140	-10	-1.051	0.4	Accepted
21	11	146	149	-2	-0.086	0.9	Accepted
21	31	169	176	-7	-0.330	0.7	Accepted
21	38	181	140	41	0.728	0.5	Accepted
21	48	192	166	27	24.72	0.0	**Rejected**
25	31	151	170	-19	-0.832	0.4	Accepted
25	34	103	117	-13	-0.427	0.7	Accepted
25	38	108	134	-25	-1.122	0.3	Accepted
25	43	140	130	11	0.543	0.6	Accepted
30	11	151	164	-13	-0.373	0.7	Accepted
30	38	174	155	19	0.269	0.8	Accepted
30	39	305	166	139	0.955	0.4	Accepted
30	45	116	150	-34	-1.594	0.2	Accepted

30	48	172	181	-9	-0.345	0.7	Accepted
35	38	166	146	19	1.316	0.2	Accepted
35	48	167	172	-5	-0.228	0.8	Accepted
38	8	223	203	20	0.406	0.7	Accepted
38	11	229	208	21	0.406	0.6	Accepted
38	16	206	217	-11	-0.232	0.8	Accepted
38	21	185	209	-24	-1.273	0.3	Accepted
38	25	233	222	10	0.097	0.9	Accepted
38	30	240	201	39	0.848	0.4	Accepted
38	31	251	235	16	0.652	0.5	Accepted
38	32	291	236	55	2.639	0.0	**Rejected**
38	38	275	198	76	1.904	0.1	Accepted
38	45	68	194	-126	-3.918	0.1	Accepted
38	47	189	214	-25	-0.546	0.6	Accepted
38	48	297	224	72	3.457	0.0	**Rejected**
38	49	173	212	-39	-0.853	0.4	Accepted
39	11	267	269	-2	-0.039	0.9	Accepted
39	31	443	296	147	2.252	0.0	Accepted
39	38	158	260	-102	-3.763	0.1	Accepted
39	48	631	286	345	3.171	0.1	Accepted

From the table it is seen that only seven (8) out of the eighty five (85) combinations of geological formations and soil types (about 9%) were rejected by the hypothesis that the prediction model fits. This is a clear indication of the acceptability of the model.

5. Conclusion

This study provides the TGDR measurement results for Pahang state Malaysia which were applied to develop a model for statistical prediction of gamma dose rates based on geological formations and soil types. The model was given by the equation TGDR = $0.580(G_D) + 0.311(S_D)$. The method could be used to predict gamma dose rates in areas with difficult access. Also, it may be used to predict gamma dose rate wherever similar geological formation and soil types exist. The measured and the predicted mean TGDR for Pahang state were found to be 176 nGy h^{-1} and 157 nGy h^{-1} respectively.

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