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ORIGINAL ARTICLE

Radiological hazard associated with natural radionuclide concentrations in the northern part of Pahang state Malaysia

H. T. Gabdo · A. T. Ramli · M. A. Saleh · M. S. Sanusi · N. N. Garba · A. S. Aliyu

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Abstract Radiological studies to determine the health hazard associated with concentrations of natural radionuclides ^{226}Ra, ^{232}Th and ^{40}K in soils of northern part of Pahang state Malaysia were conducted. In situ measurement for external gamma radiation and soil samples was taken from different locations covering the entire districts of the study area. The in situ measurements were conducted using NaI[Ti] detector. The mean terrestrial gamma dose rate (TGDR) was found to be 185 ± 7 nGy h^{-1}. The soil samples were measured using high-purity germanium detector (HPGe) and analyzed using Genie2000 software. The results obtained shows that the mean activity concentrations of the radionuclides ^{226}Ra, ^{232}Th and ^{40}K in the area were 117 ± 4, 151 ± 5 and 622 ± 57 Bq kg^{-1}, respectively. The Radium equivalent activities (R_{eq}), External hazard index (H_{ex}) and Annual Effective Dose (AED) out doors were also found to be 380 Bq kg^{-1}, 1.027 and 0.210 mSv year^{-1}, respectively. The results were compared with values given in United Nations Scientific Committee on the Effects of Atomic Radiation (2000).

Keywords Natural radioactivity concentrations · Annual effective dose · External hazard index

H. T. Gabdo (✉) · A. T. Ramli · M. A. Saleh · M. S. Sanusi · N. N. Garba · A. S. Aliyu
Department of Physics, Faculty of Sciences, Universiti Teknologi Malaysia (UTM), Skudai Johor, Malaysia
e-mail: tghamman2@gmail.com

H. T. Gabdo
Department of Physics, Federal College of Education, Yola, Nigeria

M. A. Saleh
Department of Petroleum and Renewable Energy, University Teknologi, Skudai Johor, Malaysia

Introduction

Naturally occurring radiation has led to the performance of extensive surveys in many countries of the world. The United Nations Scientific Committee on the Effect of Atomic Radiation (United Nations Scientific Committee on the Effects of Atomic Radiation 2000) reported that the mean terrestrial gamma dose rate in the world is 59 nGy h^{-1}. Malaysia has a mean value of 92 nGy h^{-1}. The world mean activity concentration of ^{226}Ra, ^{232}Th and ^{40}K is 32, 45 Bq and 420, respectively, with Malaysian average of 66, 82, and 310 Bq kg^{-1}, respectively (United Nations Scientific Committee on the Effects of Atomic Radiation 2000, Annex B).

Most of the radioactivity in the terrestrial environment, whether it is natural or man-made, is bound to the components of the soil (Ramli et al. 2005). 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 (Eisenbud 1964). For instance, soil derived from granite 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 (Malanca et al. 1996; Ramli et al. 2003).

The concentrations of ^{232}Th, ^{226}Ra and ^{40}K vary widely depending on the location (United Nations Scientific Committee on the Effects of Atomic Radiation 2000). The majority (95 %) of the external gamma dose rate above typical soils arises from primordial radionuclides incorporated in the soil (Klein and Hurlbut 1985). In addition, soil acts as a source of transfers of radionuclides to plants and animals; hence, it is the basic indicator of the radiological status of the environment. These radionuclides take part in

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several biogeochemical processes that determine their mobility and availability for biological uptake (Mandic et al. 2010).

Soils are naturally radioactive, primarily because of their mineral content. The main radionuclides in soils are ^{226}Ra, ^{232}Th and their decay products and ^{40}K. The radioactivity varies from one soil type to the other depending on the mineral makeup and composition. The higher concentrations of uranium, thorium and potassium are associated with soil developed from acid intrusive rocks and clay (Kogan et al. 1971; Saleh et al. 2013c) and probably, a majority of uranium is associated with the phosphates sands and clays of these formations (Roessler et al. 1993). The concentration of these radionuclides determines the level of radiological health hazard associated with the soils of an area.

The main objective of this work is to determine the terrestrial gamma dose rate (TGDR) and ^{226}Ra, ^{232}Th and ^{40}K concentrations in environmental samples of soils collected from the study area to estimate the radiological hazards associated with these concentrations in the soils.

Materials and methods

Study area

Pahang is the largest State in Peninsular Malaysia and the third largest in Malaysia after Sabah and Sarawak. The study area is the northern part of Pahang state Malaysia. It is made up of five districts which are Cameron Highland, Lipis, Jerantut, Temerloh and Raub. It is an area with large agricultural activities and some mining activities and is located between latitudes 3°30′00″N and 4°48′00″N and longitudes 101°30′00″ and 103°0′00″E. The main agricultural products are palm oil and rubber. The area is overlaid by 20 soil types as shown in Fig. 1 and described in Table 1.

The area has mainly seven underlying geological formations Cretaceous–Jurassic, Triassic, Permian, Carboniferous, Devonian, Silurian–Ordovician and Acid Intrusive as shown in Fig. 2 and described in Table 2.

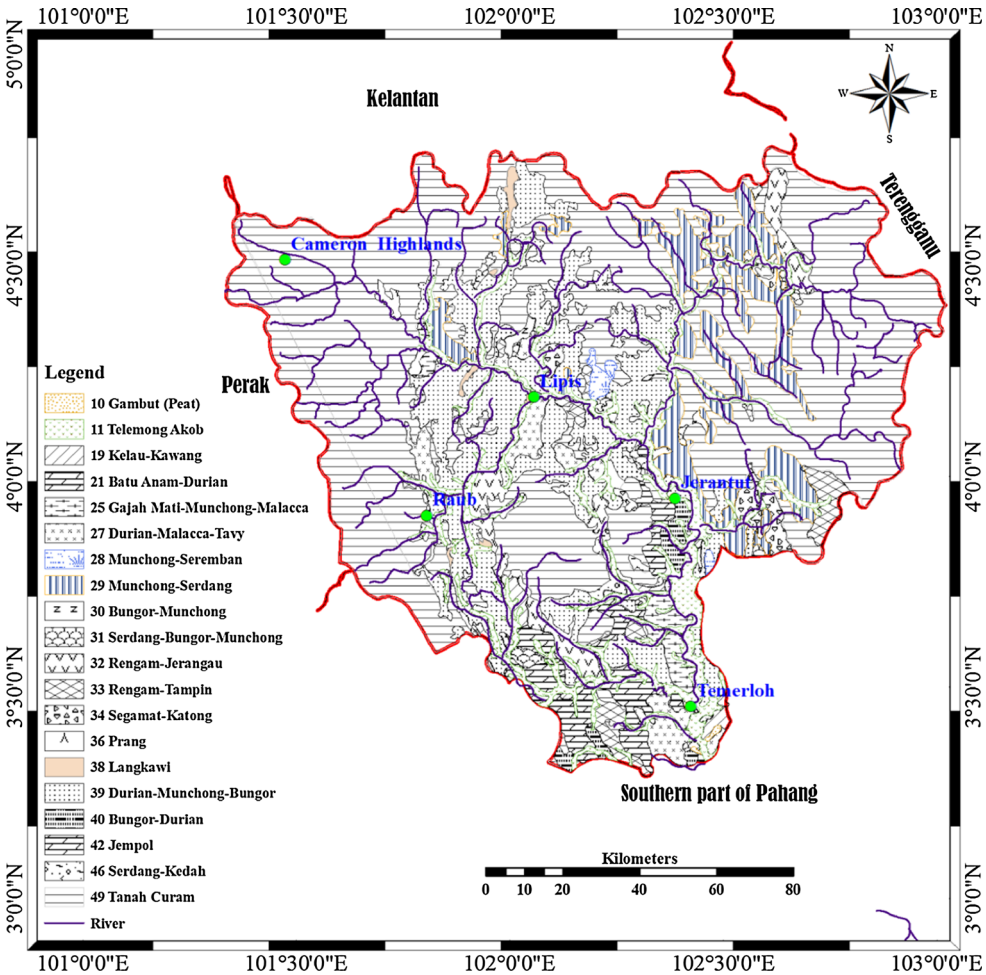

Fig. 1 Soil map of the study area (Ministry of Agriculture and Fisheries Malaysia 1968)

Table 1 Soil types in northern Pahang state

S/n	Soil type	Local name	FAO/UNESCO unit
1	(10)	Gambut (Peat)	Dystric Histosols
2	(11)	Telemong Akob–Tanah Lanar Tempatan	Dystric Fluvisols–Dystric Gleysol
3	(19)	Kelau–Kawang	Ferric Acrisols–Haplic Acrisol
4	(21)	Batu Anam–Durian	Orthic Acrisols–Ferric Acrisols
5	(25)	Gajah Mati–Munchong–Malacca	Plinthic Ferralsols–Plinthic Ferralsols
6	(27)	Durian–Malacca–Tavy	Ferric Acrisols–Plinthic Ferralsols–Plinthic Ferralsols
7	(28)	Munchong–Seremban	Orthic Ferralsols
8	(29)	Munchong–Serdang	Orthic Ferralsols–Ferric Acrisols
9	(30)	Bungor–Munchong	Ferric Acrisols–Orthic Ferralsols
10	(31)	Serdang–Bungor–Munchong	Ferric Acrisols–Ferric AcrisoIs–Orthic Ferrasols
11	(32)	Rengam–Jerangau	Dystric Nitosols–Orthic Ferrasols
12	(33)	Rengam–Tampin	Dystric Nitosols–Ferric Acrisols
13	(34)	Segamat–Katong	Rhodic Ferralsols–Xanthic ferralsols
14	(36)	Prang	Rhodic Ferralsols
15	(38)	Langkawi	Langkawi
16	(39)	Durian–Munchong–Bungor	Ferric Acrisols–Orthic Ferralsols–Ferric Acrisols
17	(40)	Bungor–Durian	Ferric Acrisols–Ferric Acrisols
18	(42)	Jempol	Rhodic Ferralsols
19	(46)	Serdang–Kedah	Ferric Acrisols
20	(49)	Tanah Curam	Steep land

Measurement of terrestrial gamma dose rates

Basically there were two methods adopted for this study; these methods include direct measurement for terrestrial gamma dose rate (TGDR) outdoors using a gamma survey meter and the second method to calculate the gamma dose rate from the activity concentrations of ^{238}Ra, ^{232}Th and ^{40}K using the conversion factors adopted by (United Nations Scientific Committee on the Effects of Atomic Radiation 2000). The TGDR was measured 1 m above the ground from various locations with the survey meter. The measurement points were chosen based on the soil map and geology map of the area. 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 80 and 1.2 MeV (Saleh et al. 2013b); this range 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 (Ramli et al. 2005). Global positioning system receiver Garmin (GPSmap 76) was used to record latitude and longitude of each measurement point (Fig. 3).

Sample collection

Using the delineated map (Figs. 1, 2), the top surface soil of the first 5 cm in depth is scraped off and discarded to remove traces of contamination due to human activities (Miller and Dohahue 1997). Soil samples were then collected from a depth of about 10 cm. The samples were packaged in polyethylene bag. Sixty soil samples were collected with a weight of 2 kg each. The samples were then taken to the laboratory for preparation and analysis.

Sample preparations

The samples were dried in an oven at 110 °C for 24 h. They were homogenized by grinding using a grinding machine which is cleaned each time before using it for another soil sample. A 250 μm sieved mounted on a sieving machine available at UTM Nuclear Laboratory was used for sieving the grinded samples. Weight samples were placed in Marinelli beakers which were completely sealed for at least one month to allow for radioactive equilibrium to be reached. This is necessary to ensure that the radon gas is confined within the volume and that the daughter will also remain in the sample (Snoor et al. 2001).

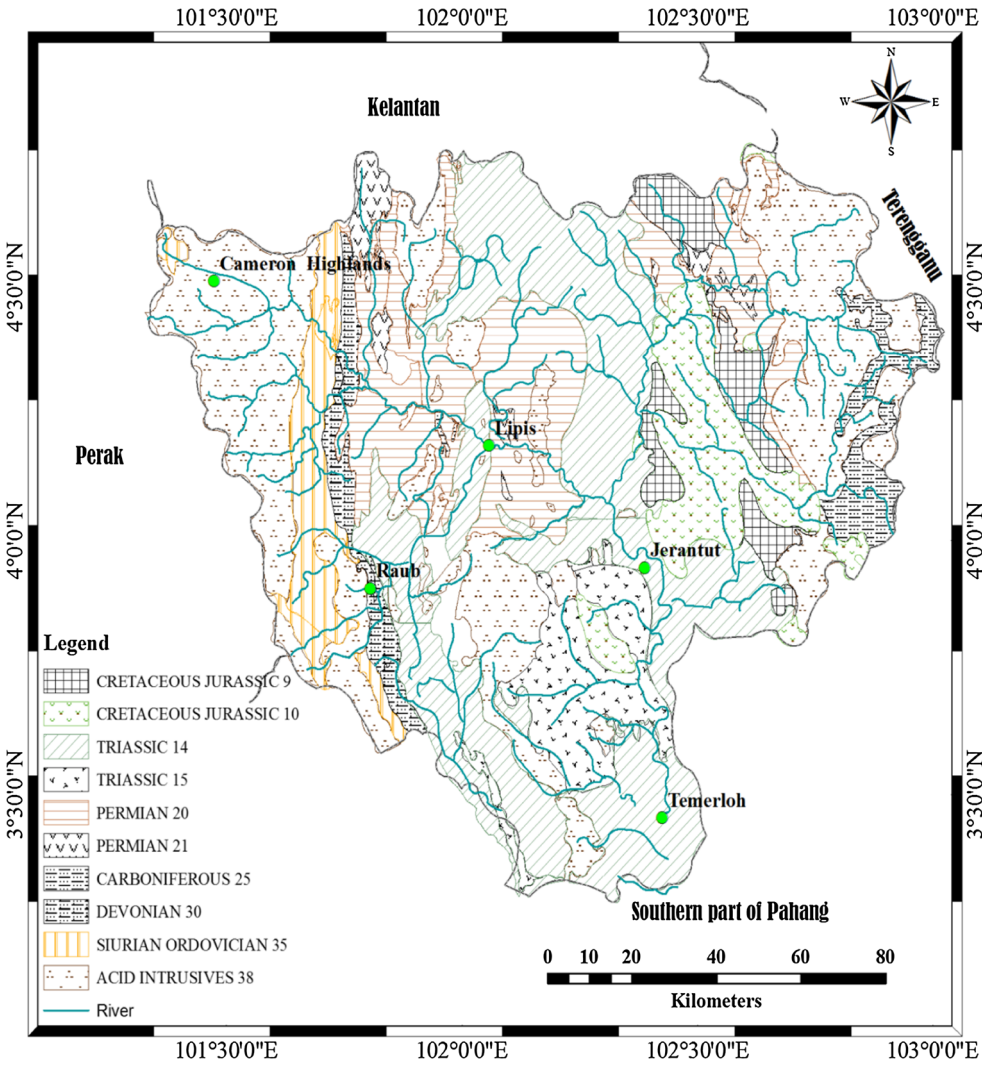

Fig. 2 Geology map of the study area (Department of Geological Survey Malaysia 1985)

Table 2 Geology types in northern Pahang state

Geological label	Geological name	Composition
G9	Cretaceous–Jurassic	Composed of thick, cross-bedded sandstone with subordinate conglomerate and shale/mudstone
G10	Cretaceous–Jurassic	Cretaceous–Jurassic (9) with metamorphic and sedimentary rocks of sandstone/metastone
G14	Triassic	Composed of interblended sandstone, siltstone and shale; widespread volcanic
G15	Triassic	Triassic (14) with extrusive rocks deposits of acid to intermediate volcanic
G20	Permian	Composed of shale, slate, and phyllite with subordinate schist and sandstone
G21	Permian	Permian (20) with extrusive rocks deposits of intermediate to basic volcanic
G25	Carboniferous	Composed of phyllite, slate and sandstone; argillaceous rock are commonly carbonaceous. Locally prominent development of limestone
G30	Devonian	Composed of phyllite, schist and slate; limestone and sandstone locally prominent
G35	Silurian–Ordovician	Schist, phyllite, slate and limestone. Minor intercalations of sandstone and volcanic
G38	Acid intrusive	Composed of undifferentiated igneous rock with acid intrusive

Sample analysis

Gamma activities were measured using spectroscopy with a coaxial high-purity germanium detector (GC2018-7500 SL). It has a relative efficiency of 20 %, and a resolution of 1.8 keV for the 1332 keV gamma-ray emission of ^{60}Co; Genie 2000 software (VI.3) from Canberra was used to analyze the spectra. The energy calibration was done using

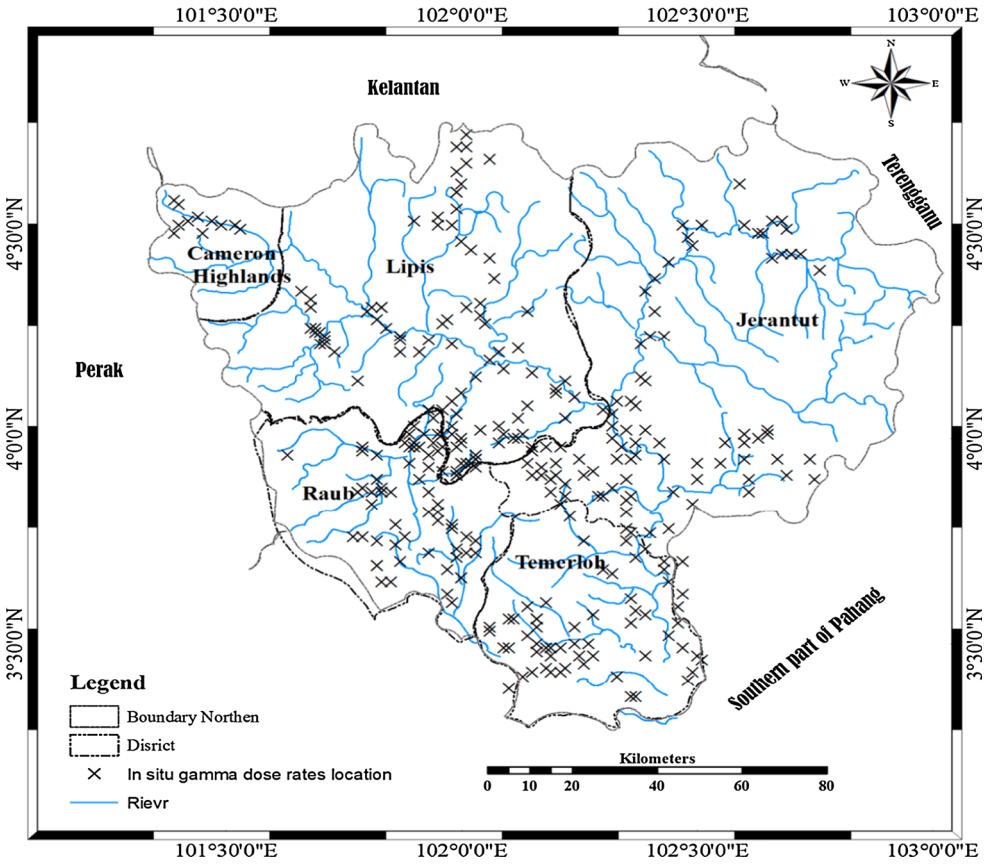

Fig. 3 Survey point locations of the study area

Table 3 Summary of external gamma dose rates in each district of the study area

District	Gamma dose rate (nGy h^{-1})				
	N	Mean	SE	SD	Range
Cameron Highland	11	285	13	42	222–350
Raub	85	235	17	158	26–750
Lipis	65	135	8	68	46–302
Temerloh	62	192	14	111	44–511
Jerantut	90	158	9	81	35–435
Mean		185	7	117	

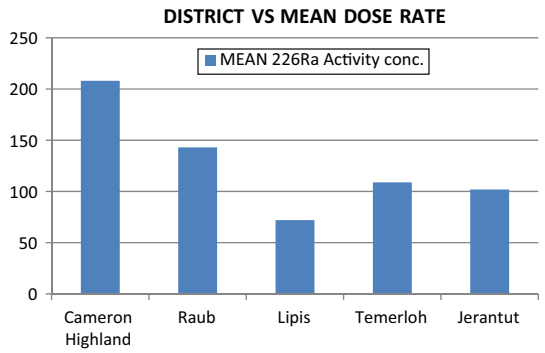

Fig. 4 Distributions of mean dose rate in the district of the study area

a point source whereas efficiency was calibrated using a 500 mL multi-nuclide standard solution. A marinelli beaker full with de-ionized water was counted to strip the background from the samples. The value of Minimum Detectable Activity (MDA) was 13 Bq kg^{-1} for ^{40}K, 1 Bq kg^{-1} for ^{226}Ra and 2 Bq kg^{-1} for ^{232}Th for a counting time of 21,600 s (International Atomic Energy Agency IAEA 1989; International Atomic Energy Agency IAEA 2003; Saleh et al. 2013a).

The activity of ^{226}Ra was determined based on gamma ray emissions of ^{214}Pb (352 keV) and ^{214}Bi (609); ^{232}Th activity was determined based on the emissions of ^{208}Tl (583.1 keV) and ^{228}Ac (911.2 keV) and that of ^{40}K was determined directly from the gamma emission energy of 1461.8 keV. The concentrations of ^{226}Ra and ^{232}Th were calculated from the weighted mean activity values determined for various emissions. IAEA Soil 6 was used for quality control and assurance.

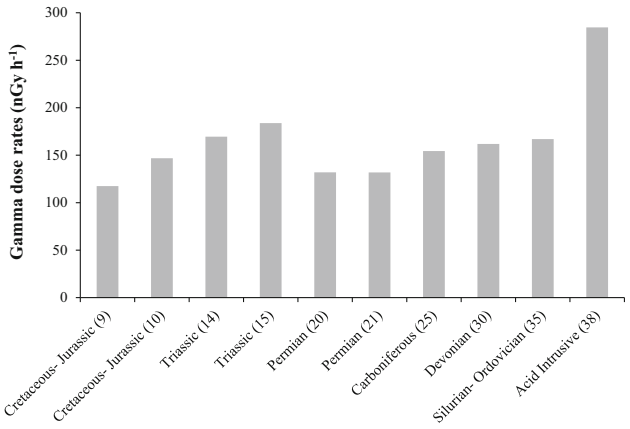

Fig. 5 Mean gamma dose rate and geological formation in the study area

Results and discussion

External gamma dose rates

Two methods have been used to evaluate external exposures in this study. The first method was direct measurement of external gamma dose rate; the readings were taken at 313 locations in the study area at 1 m above the ground using NaI [Ti] gamma detector (Ludlum 19). The external gamma dose rate ranges from 26 to 750 nGy h^{-1} with a mean value of 185 nGy h^{-1}. The district of Cameron Highland has the highest mean dose rate of 285 ± 13 nGy h^{-1} while the district of Lipis has the lowest mean dose rate of 135 ± 8 nGy h^{-1} (Table 3; Fig. 4).

Table 4 and Fig. 5 show the mean dose rate in each geological formation of the study area. Geology type 38 (acid intrusive) has the highest mean gamma dose rate of 285 ± 20 nGy h^{-1} while geology type 9 (Cretaceous–Jurassic) has the lowest gamma dose rate of 118 ± 16 nGy h^{-1}.

Table 5 and Fig. 6 show the distributions of mean dose rate and soil types in the study area. Soil type 36 (Prang) has the highest mean gamma dose rate of 298 ± 41 nGy h^{-1} while soil type 27 (Durian–Malacca–Tavy) has the lowest mean gamma dose rate of 94 ± 2 nGy h^{-1}. An Isodose map for the measured gamma dose rate was plotted using ArcGIS 9.3 software; this is shown in Fig. 7.

The second method was based on measured activity concentrations in soil samples. The activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in soil were obtained using the HPGe gamma spectrometer. The methodology used for the derivation of the gamma dose rates from the concentrations was adopted from United Nations Scientific Committee on the Effects of Atomic Radiation (2000) using Eq. (1);

$$D(\text{nGy h}^{-1}) = (0.462A_{\text{Ra}} + 0.604A_{\text{Th}} + 0.0417A_{\text{K}}) \quad (1)$$

Figure 5 shows the observed relationships between the calculated dose rate and the measured dose rate. The coefficient of correlation was found to be $R = 0.969$, which shows a very good correlation between measured gamma dose rates and the calculated gamma dose rates.

Activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K

The soil samples were measured using the (HPGe) detector. A total of 60 soil samples were analyzed for quantitative determination of ^{226}Ra, ^{232}Th and ^{40}K. The measured activity concentrations of ^{226}Ra range from 11 to 436 Bq kg^{-1} with a mean value of 117 ± 4 Bq kg^{-1} while ^{232}Th activity concentrations range from 15 to 483 Bq kg^{-1} with a mean value of 151 ± 5 Bq kg^{-1}. The activity concentration of ^{40}K ranges from 57 to 4050 Bq kg^{-1} with a mean value of 622 ± 57 Bq kg^{-1} (Table 6). The World average concentrations are 32 and 45 Bq kg^{-1} for ^{226}Ra and ^{232}Th, respectively. The typical ranges are 16 to 110 Bq kg^{-1} for ^{226}Ra and 11 to 64 Bq kg^{-1} for ^{232}Th. The

Table 4 Descriptive analysis of mean gamma dose rates and geological formations in the study area

Geology type	*N*	Mean	SD	SE	95 % confidence		Minimum	Maximum
					Lower bound	Upper bound		
9	10	117.45	49.428	15.630	82.09	152.81	48	184
10	13	146.81	90.548	25.114	92.09	201.53	65	409
14	120	169.49	102.029	9.314	151.04	187.93	35	511
15	31	183.86	72.757	13.068	157.17	210.55	70	339
20	40	132.00	62.583	9.895	111.98	152.01	53	274
21	4	131.86	61.566	30.783	33.89	229.82	67	190
25	2	154.43	104.581	73.950	785.20	1094.05	80	228
30	15	161.89	90.226	23.296	111.93	211.86	44	383
35	16	166.93	91.973	22.993	117.92	215.94	26	302
38	62	284.58	157.291	19.976	244.64	324.53	36	750
Mean		185.24	117.262	6.628	172.20	198.28		

Table 5 Descriptive analyses for mean gamma dose rates and soil type in the study area

Soil type	*N*	Mean	SD	SE	95 % confidence		Minimum	Maximum
					Lower bound	Upper bound		
10	2	155.40	63.210	44.696	412.52	723.32	111	200
11	51	185.51	80.819	11.317	162.78	208.25	44	479
19	8	228.78	135.955	48.068	115.12	342.44	90	420
21	20	212.23	127.404	28.488	152.60	271.85	92	511
25	1	163.13	–	–	–	–	163	163
27	4	94.07	4.020	2.010	87.67	100.47	89	99
28	1	133.76	–	–	–	–	134	134
29	24	116.09	38.733	7.906	99.74	132.45	37	190
30	2	154.97	116.116	82.106	888.29	1198.23	73	237
31	5	129.20	48.867	21.854	68.52	189.87	65	196
32	28	297.21	164.488	31.085	233.43	361.00	70	750
33	4	228.38	90.535	45.268	84.31	372.44	104	298
34	7	108.44	80.163	30.299	34.30	182.58	35	237
36	2	297.98	58.442	41.325	227.11	823.06	257	339
38	7	156.91	99.413	37.575	64.97	248.85	78	352
39	80	157.55	98.412	11.003	135.65	179.45	44	479
40	1	130.50	–	–	–	–	131	131
42	2	114.19	63.056	44.588	452.35	680.73	70	159
46	5	147.90	91.715	41.016	34.02	261.78	36	268
49	58	210.15	136.009	17.859	174.39	245.91	26	750
Mean		185.39	117.420	6.648	172.31	198.47		

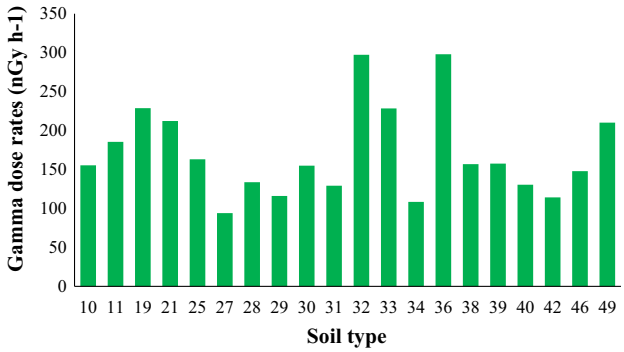

Fig. 6 Mean dose rate and soil types in the study area

world average concentration is 420 Bq kg^{-1} for ^{40}K, and the typical range is 140 to 850 Bq kg^{-1} for ^{40}K (United Nations Scientific Committee on the Effects of Atomic Radiation 2000). The highest ^{226}Ra and ^{232}Th mean activity concentrations were found in the district of Cameron Highland with values 208 ± 7 and 210 ± 7 Bq kg^{-1}, respectively, whereas the highest mean activity concentration of ^{40}K was found in the district of Raub with a value of 759 ± 75 Bq kg^{-1} (Table 6; Fig. 9).

Table 7 and Fig. 10 show the distribution of activity concentration over geological formations in the study area. Geology type G38 (Acid intrusive) has the highest mean activity concentration of ^{226}Ra, ^{232}Th and ^{40}K radionuclides with values 206 ± 26.5, 294.7 ± 36.9 and 1068.5 ± 268.4 Bq kg^{-1}, respectively. The lowest mean activity concentration of ^{226}Ra, ^{232}Th and ^{40}K is from geological formation G25 (Carboniferous), G15 (Triassic) and G21 (Permian) with values 39 ± 1, 67.7 ± 15 and 323 ± 3 Bq kg^{-1}, respectively.

Radiological hazard indices

The radiological hazard indices associated with this study are calculated and shown in Table 8 with the distribution shown in Fig. 11. This includes the following:

Annual effective dose rate (AED)

To estimate the annual effective dose (AED), took into account the conversion coefficient, (0.7 Sv Gy^{-1}) from the absorbed dose in air to effective dose and the outdoor occupancy factor (~20 %) (United Nations Scientific Committee on the Effects of Atomic Radiation 2000). It is calculated using Eq. (2).

$$\mathrm{AED(mSv\ year^{(-1)})} = D(\mathrm{nGy\ h^{(-1)}}) \times 8760\ \mathrm{h} \times 0.2 \times 0.7(\mathrm{Sv\ Gy^{(-1)}}) \times 10^{(-6)} \quad (2)$$

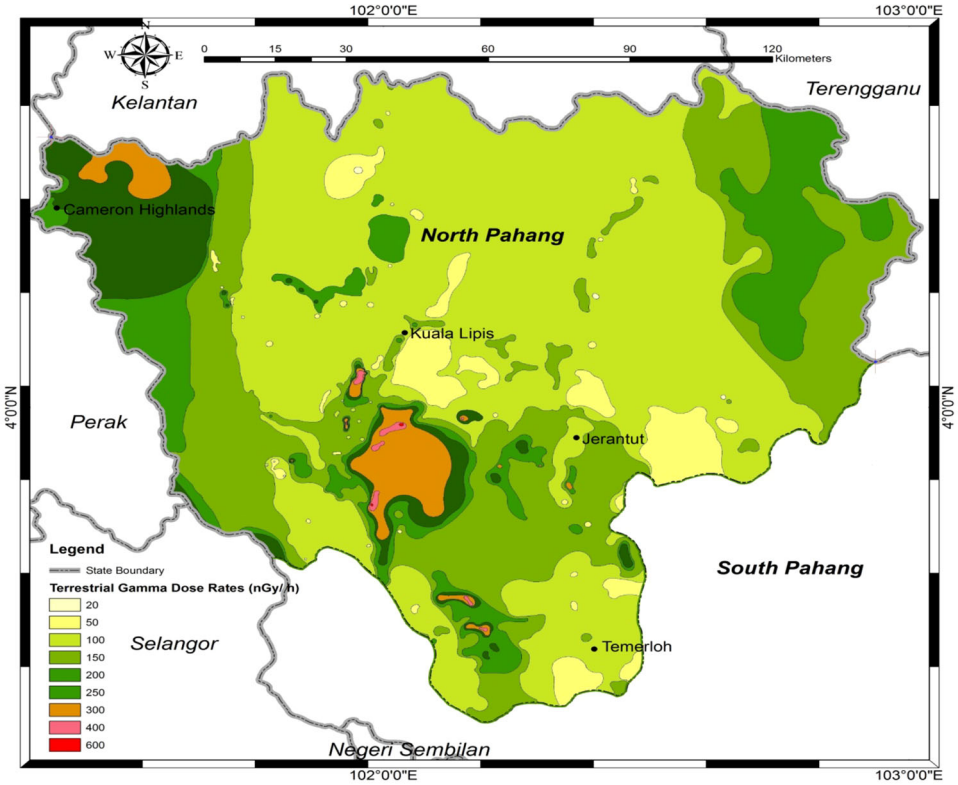

Fig. 7 Isodose map of the study area

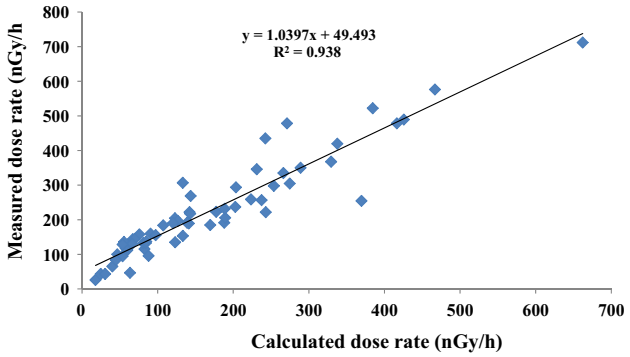

Fig. 8 The calculated gamma dose rate verses measured dose rate

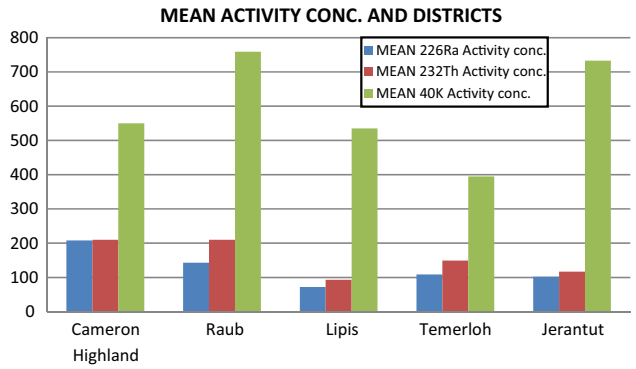

Fig. 9 Distributions of mean activity concentrations of radionuclides in the districts of the study area

Table 6 Summary of activity concentrations of natural radionuclides in each district of the study area

District	^{226}Ra (Bq kg^{-1})		^{232}Th (Bq kg^{-1})		^{40}K (Bq kg^{-1})	
	Mean	Range	Mean	Range	Mean	Range
Cameron Highland	208 ± 7	183–233	210 ± 7	126–266	550 ± 56	188–1050
Raub	143 ± 4	11–264	210 ± 7	15–452	759 ± 75	90–2170
Lipis	72 ± 2	17–175	93 ± 3	18–227	535 ± 53	217–1060
Temerloh	109 ± 4	31–331	149 ± 5	23–442	395 ± 40	57–1070
Jerantut	102 ± 3	30–436	117 ± 3	30–483	733 ± 54	144–4050
Mean	117 ± 4	11–436	151 ± 5	15–483	622 ± 57	57–4050

Table 7 Summary of activity concentrations of natural radionuclides and geology type

Geological formations	^{226}Ra (Bq kg^{-1})		^{232}Th (Bq kg^{-1})		^{40}K (Bq kg^{-1})	
	Mean	Range	Mean	Range	Mean	Range
Cretaceous–Jurassic (G9)	54.7 ± 9.5	38–71	85.3 ± 26.3	48–136	332 ± 81	175–446
Cretaceous–Jurassic (G10)	128	128–128	129	129–129	779	779–779
Triassic (G14)	104.4 ± 13.3	30–232	136.9 ± 20.2	30–404	495.3 ± 65.5	92–1073
Triassic (G15)	64 ± 13.6	40–87	67.7 ± 15	41–93	610.3 ± 156.5	339–881
Permian (G20)	62.7 ± 15.7	17–175	77.6 ± 22.7	18–227	492.2 ± 89.1	57–1063
Permian (G21)	78 ± 3	74–84	179 ± 6	97–333	323 ± 3	174–537
Carboniferous (G25)	39 ± 1	38–40	80 ± 3	76–85	727 ± 7	571–883
Devonian (G30)	91.8 ± 31.2	18–164	83.2 ± 30.2	19–188	463.8 ± 130.9	114–888
Silurian–Ordovician (G35)	112 ± 64.9	11–233	92.3 ± 49.7	15–185	364.7 ± 142.1	90–565
Acid Intrusive (G38)	206.8 ± 26.5	53–436	294.7 ± 36.9	73–483	1068.5 ± 268.4	131–4053

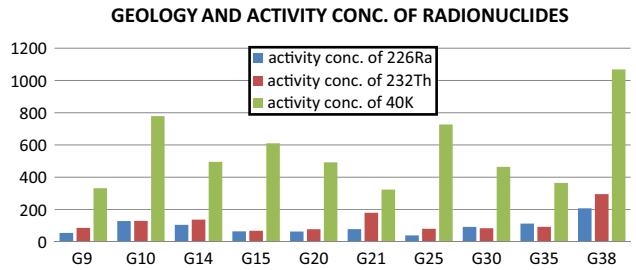

Fig. 10 Distributions of mean activity concentrations of radionuclides and geology of the study area

The mean value obtained was found to be 0.210 mSv year^{-1} which is three times the world outdoor average value of 0.07 mSv year^{-1} (United Nations Scientific Committee on the Effects of Atomic Radiation 2000).

Radium equivalent activity (R_{eq}) is used to assess the gamma radiation hazards associated with materials that contain ^{226}Ra, ^{232}Th and ^{40}K. This is calculated using Eq. (3).

$$\mathrm{Ra_{eq}} = \left(\mathrm{Bq\ kg^{-1}}\right) = (A_K \times 0.077) + (A_{Ra}) + (A_{Th} \times 1.43) \quad (3)$$

The mean value was found to be 380 Bq kg^{-1} (Beretka and Matthew 1985). This is higher than the recommended value of 370 Bq kg^{-1} (United Nations Scientific Committee on the Effects of Atomic Radiation 2000).

External Hazard Index (H_{ex}) is defined in terms of external hazard index or outdoor radiation hazard index and denoted by H_{ex}. It can be calculated using Eq. (4)

$$H_{ex} = \left(\frac{A_{Ra}}{370}\right) + \left(\frac{A_{Th}}{259}\right) + \left(\frac{A_K}{4810}\right) \quad (4)$$

where A_{Ra}, A_{Th} and A_K are activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K, respectively, in Bq kg^{-1}. The value of this index should be less than 1, for the radiation hazard to be considered acceptable to the public (Beretka and Mathew 1985). The mean value was found to be 1.027 which is slightly more than the unity value recommended.

Conclusion

The study evaluated the activity concentrations of ^{238}Ra, ^{232}Th and ^{40}K and terrestrial gamma dose rates and the corresponding radiological hazards associated in the study area. The external gamma dose rate varies from 26 to 750 nGy h^{-1} with the mean value of 185 ± 7 nGy h^{-1}. This is two times higher than the Malaysia average value of 92 nGy h^{-1} and more than three times the world average value of 59 nGy h^{-1}. The mean activity concentrations of ^{226}Ra and ^{232}Th obtained

Table 8 Radiological hazard indices in the study area

District	AED (mSv y^{-1})		Ra_{eq} (Bq kg^{-1})		H_{ex}	
	Mean	Range	Mean	Range	Mean	Range
Cameron Highland	0.302	0.218–0.355	551	394–644	1.489	1.065–1.740
Raub	0.276	0.022–0.573	502	39–1033	1.357	0.106–2.791
Lipis	0.137	0.049–0.291	246	82–523	0.665	0.221–1.411
Temerloh	0.192	0.037–0.522	352	68–974	0.952	0.184–2.630
Jerantut	0.182	0.055–0.813	325	97–1439	0.879	0.261–3.886
Mean	0.210	0.022–0.813	380	39–1439	1.027	0.106–3.886

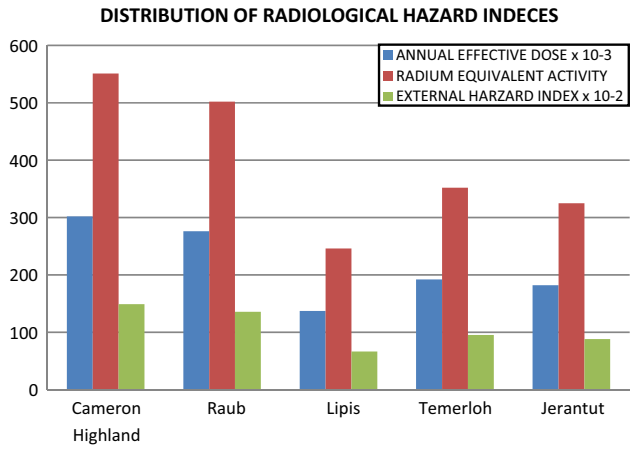

Fig. 11 Distributions of radiological hazard indices in the districts of the study area

from the study area are 117 ± 4 and 151 ± 5 Bq kg^{-1}, respectively; these are both more than three times the world average values of 32 and 45 Bq kg^{-1}, respectively, while that of ^{40}K (622 ± 57 Bq kg^{-1}) was found to be more than the world average value of 420 Bq kg^{-1}. Cameron Highland District has the highest mean activity concentrations of ^{226}Ra and ^{232}Th with values 208 ± 7 and 210 ± 7 Bq kg^{-1}, respectively, while Raub District has the highest mean activity concentration of the ^{40}K with a value of 759 ± 75 Bq kg^{-1}. Geology type 38 (acid intrusive) has the highest mean gamma dose rate of 285 ± 20 nGy h^{-1} and also the highest mean activity concentration of ^{226}Ra, ^{232}Th and ^{40}K radionuclides with values of 206 ± 26.5, 294.7 ± 36.9 and 1068.5 ± 268.4 Bq kg^{-1}, respectively, while geology type 9 (Cretaceous–Jurassic) has the lowest gamma dose rate of 118 ± 16 nGy h^{-1}. The lowest mean activity concentration of ^{226}Ra, ^{232}Th and ^{40}K is from geological formation G25 (Carboniferous), G15 (Triassic) and G21 (Permian) with values 39 ± 1, 67.7 ± 15 and 323 ± 3 Bq kg^{-1}, respectively.

The mean annual effective dose rate in the area (0.210 mSv year^{-1}) is three times the world mean outdoor annual effective dose rate of 0.07 mSv year^{-1}. The mean value for radium equivalent activity (Raeq) was found to be 380 Bq kg^{-1}. This is higher than the recommended value of 370 Bq kg^{-1}. The mean external hazard index (H_{ex}) in soil samples was 1.027 which is slightly higher than the recommended unity value. The level of health hazard due to terrestrial gamma dose rates and natural radioactivity is higher than the world average but is still within normal range, thus should not pose any significant danger to the population.

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