Air Qual Atmos Health (2016) 9:551–560
DOI 10.1007/s11869-015-0360-5

Risk analysis from naturally occurring radioactive materials in the Jamaican terrestrial environment

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Received: 30 April 2015 / Accepted: 1 July 2015 / Published online: 12 July 2015

Abstract In this work, statistics and geospatial analysis are used to investigate the hypothesis that either bauxitic soils or underlying geology increases the carcinogenic health risks to the population due to exposure from naturally occurring radioactive materials (NORM) in the soil environment over which they reside. The rationale for this study is the large distribution of bauxitic soils in Jamaica and a review of the last published 5-year cancer survey study of Jamaica. A negative health environment was defined as one where the excess lifetime cancer risk (ELCR) value exceeded the world mean value of 2.9×10^{-4} and the annual gonadal dose equivalent (AGDE) was a multiple of the acceptable level of 300 μSv/year. The excess lifetime cancer risk index in Jamaica ranges from 0.16×10^{-5} to 7.92×10^{-4} with a mean value of 1.63×10^{-4}. The mean value of the ELCR index in Jamaica was statistically significantly lower than the world mean value. The main areas of concern were the sections of the parishes of Manchester and St. Elizabeth which exhibited value of up to five (5) times the acceptable level of the ELCR index. The AGDE index showed a moderate correlation of 0.511 with a reclassified geology group (limestone and non-limestone) introduced in this study. The soils overlaying limestone formations in Jamaica were characterized by a statistically significantly higher dose rate exposure to the gonads of the population. Geological explanations for the levels of the primordial radionuclides are also discussed in this paper. The results suggested that limestone geology in Jamaica had a significantly higher mean value for both indices (ELCR and AGDE) when compared to other geologies. Since bauxitic soils predominantly overlay these rocks in Jamaica, the research hypothesis regarding the impact bauxitic soils is supported by the results of this study. The impact of geology was not significant, and probable causes are discussed.

Keywords Health · Soil · Radionuclides · Annual gonadal dose equivalent · Carcinogenic

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Introduction

The study overview

In this work, statistics and geospatial analysis are used to investigate the hypothesis that either bauxitic soils or underlying geology increases the carcinogenic health risks to the population due to exposure from naturally occurring radioactive materials (NORM) in the soil environment over which they reside. The rationale for this study is the large distribution of bauxitic soils in Jamaica and a review of the last published 5-year cancer survey study of Jamaica which showed an increase in prostate and colorectal cancers in male over the previous study. The results of previous vs study period were aged-standardized rates (ASR) 65.5 vs 78.1 per 100,000 per year for prostate cancers and ASR 13.7 vs 17.2 per 100,000 per year for colorectal cancers (Gibson et al. 2010). An ASR is a summary measure of the rate that a population would have if it had a standard age structure. Additionally, no study has been done in Jamaica to correlate the underlying soil geology with radiation risk from NORM.

The estimated lifetime attributable risks (LAR) of solid cancer incidence for a mixed population exposed to 0.1 Gy is 154 and 138 in the colon and lungs, respectively, in males and 462 and 304 in the breasts and lungs in female. These values are all per 10^5; hence, exposure to 0.1 Gy of radiation will on average induce colon and lung cancers in 0.00154 and 0.00138 % of males (Committee to Assess Health Risks from Exposure to Low Levels of Ionizing Radiation 2006).

This LAR factor is a measure of the proportion of the total risk which can be attributed to the radiation risk factor under consideration. Jamaica was ranked the 5th highest producer of bauxite in 2010 just behind Australia, China, Brazil and Guinea (Maps of the World 2014). The results on the analysis of the carcinogenic impact of bauxitic soil may therefore be applicable to other bauxite-producing countries. This paper represents the first risk-assessment study of background radiation due to the prevalence of bauxitic soils in Jamaica. The study is important since the literature on the biological effects of low-dose radiation exposure in humans has many conflicting and unresolved issues (Nussbaum and Köhnlein 1994).

Taskin et al. mapped outdoor gamma dose rate and specific activity (Bq/kg) for Ra-226, Th-232, K-40, Cs-137 and U-238 in Kirklareli and concluded that the average soil activity concentrations were within the worldwide range. In his study, some extreme values were determined and the lifetime risk of cancer doubled for most of the localities investigated. Since reliable, standardized mortality and morbidity statistics were not accessible, the study was limited to background radiation levels only (Taskin et al. 2009). The excess lifetime risks of cancer, and the annual effective gamma doses in western Mazandaran Province of Iran, were found to be higher than the global average when gamma analysis of 54 soil samples were performed (Abbaspour et al. 2010). In Nigeria, incidence of cancer from soil radioactivity found that cancer cases attributable to radiation exposure due to soil radioactivity was low, constituting between 1.3 and 9.2 % of the total reported cases (Jibiri 2001). In Kirklareli, Turkey, the excess lifetime cancer risks and outdoor gamma dose rates were determined from 230 sampling stations and soil samples taken from 177 locations. The annual effective gamma dose of Kirklareli was 144 μSv and the excess lifetime cancer risk of 5.0×10^{-4} (Taskin et al. 2009). A study in Great Britain concluded that a major portion of cancer deaths in children were associated with natural background radiation. The study also suggested that the exposure risk from natural background radiation was three times higher in the first trimester than in the third trimester of pregnancy. In this study, the effects of sociodemographic, medical confounding factors and their temporal changes were identified and separated, leading the researchers to conclude that the background radiation exerted an independent statistically significant effect (Knox et al. 1988). In the USA, it is estimated that 55 % of background radiation originates from radon and its progenies, 27 % from cosmic, terrestrial and internal exposure, with the remaining 18 % from man-made sources including medical facilities (Schonken 1991). Other studies have looked at the impact of bauxitic soils in the environment. A study in Jamaica attributed high levels of cadmium to soils found in the central parts of the island but did not examine risks based on gamma radiation (Wright et al. 2010). A recent study on the radiological hazards in soil from the bauxite deposit sites in the Dschang region of Cameroon concluded that gamma radiation above the NORM was a concern (Ndontchueng et al. 2014). In Australia, a study on the radiological consequences of amending soils with bauxite residue gypsum mixtures found a linear increase of incremental gamma dose with increasing rate of residue (Summers et al. 1993).

Overview of the biological impact of ionizing radiation in humans

The radiogenic induction of cancers is a stochastic effect and the probability of cell damage increases with dose exposure. No consensus or epidemiological evidence supports the hormesis hypothesis that low levels of radiation are beneficial to humans due to their prevalence in the environment (Loken 1987). Cancer induction is the most important somatic risk, and research has shown that there exists no threshold dose or dose rate below which there is zero risk for stochastic radiogenic damage (Gofman 1990). The theory of a linear relationship between radiation dose and its detrimental impact implies that even low doses of radiation may have a negative health effect. The biological effects to humans due to radiation may be classified as either stochastic or deterministic. Deterministic effects include a range of somatic effects such as cataracts and decreased white blood count which depends on absorbed dose, dose rate and the area of the exposed parts of the body. Stochastic effects include cancers and genetic risks. The probability of stochastic effects increases with dose, but the intensity of the effect is not a function of the absorbed dose (Limacher et al. 1998). This conclusion is based on epidemiologic studies that have shown excess cancer induction at very low doses and at very low dose rates (Nussbaum and Köhnlein 1994, 1995).

Finally, a number of researchers have investigated the impact of dust particles on human health due to particulate matter pollution and biological particles (Lu et al. 2013; Goossens 2012; Raispour et al. 2014; Kakikawa et al. 2008; Burkart et al. 2013). These dust particles also carry the primordial radionuclides investigated in this study, which finds their way into the human body via ingestion and inhalation. Additional research combining the impact of climate change on dust generation may also establish a relationship between radionuclide inhalation and climate change.

The bauxitic and geological environment in Jamaica

The central section of the island (see Fig. 1) has a blanket of terra rossa and bauxite covering the Cenozoic limestone.

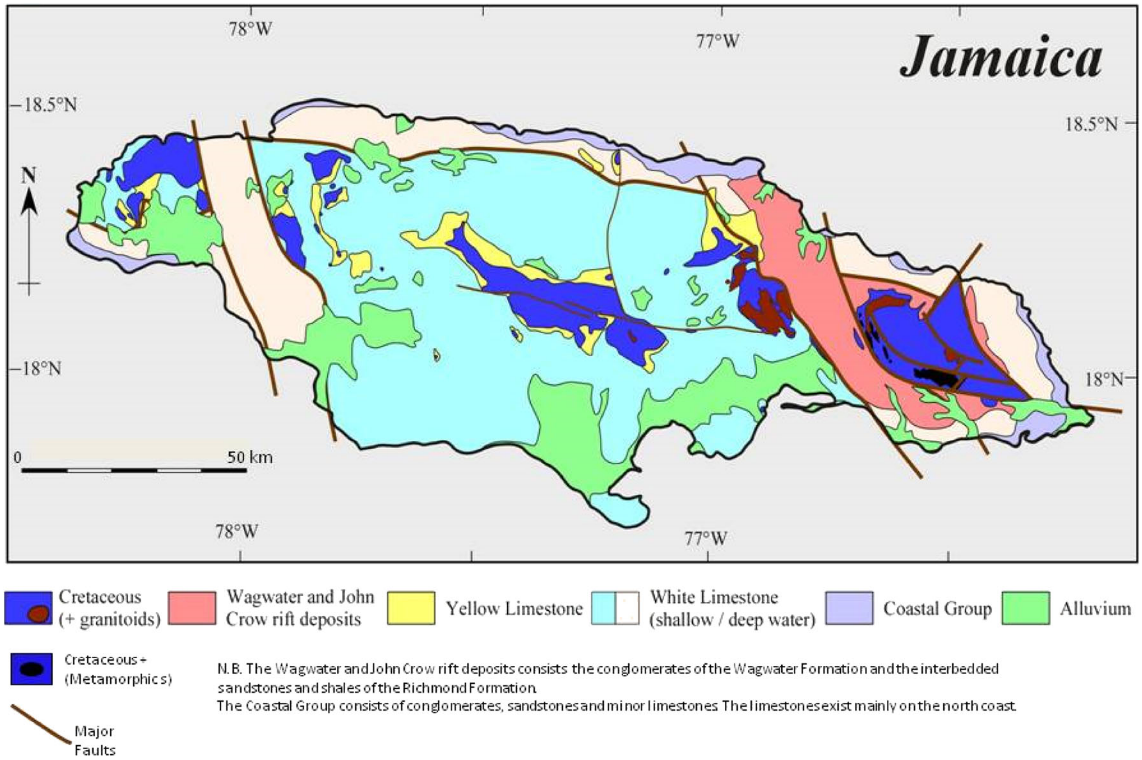

Fig. 1 Simplified geological map of Jamaica. Courtesy of the Department of Geology and Geography, University of the West Indies

In Jamaica, the majority of bauxite plants and productions are located here. Most of the central and areas in the western section of Hanover and Westmoreland are characterized as bauxitic due to the presence of more than 15 % of aluminium in the soil (The International Centre for Nuclear and Environmental Science 2014). They are classified as either terra rossa (red limestone) or rendzinas (black limestone). The red limestone occurs mainly in St. Ann, Manchester and St. Elizabeth and constitutes the bauxitic soils with red colour due to oxidation of iron. The black limestone, exposed over yellow limestone rocks, does not exhibit the red bauxite colour due to their high calcium and water component which inhibits ferric oxidation (Lalor 1996; Exploration Management Services 1958).

Material and methods

This study is a follow-up to a previously published research. Sections 2.2 to 2.6, which have been published, are reproduced here for ease of reference (Miller and Voutchkov 2014).

Health index used in risk analysis study

This study uses both the excess lifetime cancer risk (ELCR) and the annual gonadal dose equivalent (AGDE) indices to imply the carcinogenic risk faced by the population residing over bauxitic soils and specific geologies in Jamaica. The ELCR index, shown in Eq. 1, expresses the probability that at a given exposure level, the individual will develop cancer in their lifetime (Abbaspour et al. 2010). In this expression, "DL" is the expected life duration of the individual and "RF" (a 0.05 value) is used by the Internal Commission on Radiation Protection, ICRP, for stochastic effects on the public.

$$\mathrm{ELCR} = \mathrm{AEDE}_{\mathrm{out}\left(\frac{\mu\mathrm{Sv}}{\mathrm{year}}\right)} \times \mathrm{DL} \times \mathrm{RF} \quad (1)$$

The annual effective dose equivalent outdoors (AEDE in Eq. 2) is the annual effective dose received by an individual outdoors and is calculated by applying a dose conversion factor of 0.7 Sv/Gy to the absorbed dose rate "D" 1 m above ground (Kurnaz et al. 2007). The expression for D is described by Eq. 2.

$$\mathrm{AEDE}_{\mathrm{out}\left(\frac{\mu\mathrm{Sv}}{\mathrm{year}}\right)} = D \times 8760\left(\frac{h}{\mathrm{year}}\right) \times 0.2 \times 10^{-3} \times 0.7\ {}^{\mathrm{Sv}}/_{Gy} \quad (2)$$

The absorbed dose rate in air 1 m above ground (D, Eq. 3) is due to the presence of soil resident primordial radionuclide (Patra et al. 2008).

$$D\left(\frac{n\mathrm{Gy}}{h}\right) = 0.427\ \mathrm{A_U} + 0.662\ \mathrm{A_{Th}} + 0.0432\ \mathrm{A_{K40}} \quad (3)$$

The gonads (the testes in males and the ovaries in females), the active bone marrow and surface cells, are considered the organs of interest by the United Nations Scientific Committee

Table 1 Summary of specific activity of radionuclides and their uncertainties (Unct) by sampling location

LocID	Latitude (degrees)	Longitude (degrees)	K-40 (Bq/kg)	Unct ±	U-238 (Bq/kg)	Unct ±	Th-232 (Bq/kg)	Unct ±
1	18.28775	−78.2947	355.1	24.89	181.24	10.81	62.58	4.893
2	18.3868	−78.2	346.11	23.72	48.864	8.717	12.139	4.104
3	18.261	−78.1357	246.45	25.23	87.688	9.381	35.64	4.595
4	18.261	−78.1357	316.09	47.5	98.79	17.931	96.552	9.626
5	18.42814	−78.0339	327.71	34.13	50.46	12.48	63.67	6.79
6	18.2393	−77.9764	124.46	21.39	26.39	7.85	72.58	4.55
7	18.51084	−77.8813	195.52	37.47	20.37	12.83	Below MDA	N/A
8	18.35114	−77.8774	118.25	27.82	207.17	12.21	171.91	7.08
9	18.02546	−77.8569	198.12	28.95	71.67	10.33	4.664	5.055
10	18.00103	−77.7871	353.86	33.17	373.77	14.12	69.07	6.12
11	17.89158	−77.7274	175.76	27.83	38.974	9.885	66.591	5.582
12	18.168	−77.7162	130.89	26.6	64.064	5.23	97.669	10.215
13	18.05521	−77.7083	335.78	29.31	202.26	12.21	78.633	5.849
14	18.49537	−77.6684	242.35	24.23	119.07	9.48	69.244	4.89
16	18.18424	−77.6102	96.15	32.75	83.71	12.08	108.58	6.83
17	18.0024	−77.5548	389.79	34.01	663.38	20.12	132.66	7.11
18	18.12871	−77.5418	87.47	40.29	409.19	17.75	43.63	7.31
19	18.22769	−77.5292	71.518	30.118	177.15	12.58	116.42	6.73
20	18.24553	−77.5262	233.51	33.27	39.803	11.696	14.596	5.976
21	18.21713	−77.5183	289.32	30.88	66.94	11.35	15.63	5.64
22	18.06682	−77.5121	174.02	26.15	590.15	16.95	89.224	5.374
23	18.35455	−77.5096	63.054	35.921	234.79	15.08	79.142	7.05
24	18.0678	−77.5067	140.78	24.13	451.8	14.06	96.9311	5.236
26	18.07613	−77.4964	244.24	25.97	444.31	14.43	136.9	5.94
27	18.06831	−77.4954	193.63	26.45	418.37	14.18	54.807	5.064
28	18.47011	−77.4645	374.42	30.54	38.412	10.89	57.539	5.546
29	18.47	−77.42	75.803	23.333	83.779	9.285	54.103	4.683
30	18.03359	−77.3941	134.02	26.74	58.68	10.191	36.916	5.342
31	18.4003	−77.365	184.59	33.87	170.61	13.08	97.13	6.81
32	17.91685	−77.3637	210.35	31.82	76.63	12.113	74.135	6.321
33	18.3087	−77.3555	133.02	35.45	213.86	14.18	131.16	7.28
34	18.14435	−77.3336	260.52	26.71	42.308	9.785	14.631	4.662
35	18.46747	−77.2968	29.573	20.981	133.19	9.16	10.263	3.77
37	17.90725	−77.2466	227.45	18.97	15.974	6.403	14.19	3.147
38	17.92539	−77.2441	235.52	24.52	20.706	9.107	25.216	4.481
39	17.88658	−77.2426	518.4	27.1	26.84	9.293	7.1	4.443
40	17.89617	−77.2408	212.4	14.54	54.875	5.416	18.456	2.7
41	18.0402	−77.2406	131.43	36.35	157.37	14.34	34.77	6.88
42	17.81007	−77.2339	466.47	27.53	53.529	10.2	27.138	4.711
43	18.40365	−77.1118	193.99	31.64	22.241	11.356	7.382	5.537
44	17.94083	−77.11	463.2	24.25	45.118	8.211	18.276	4.145
45	18.2928	−77.107	313.66	37.65	146.64	14.39	79.43	7.434
46	18.28033	−77.1	Below MDA	N/A	93.289	11.053	129.84	6.51
47	18.17445	−77.0545	130.63	18.58	30.429	6.603	38.431	3.635
49	18.14355	−77.026	77.152	18.537	24.567	6.648	20.022	3.461
50	18.10212	−76.9483	559.33	28.19	50.36	9.31	25.652	4.789
51	18.09	−76.9476	344.97	32.16	521.78	17.46	45.225	5.727
52	18.068	−76.9339	114.04	41.67	293.42	16.89	63.6	8.11
53	18.20888	−76.8141	424.36	25.44	22.61	9.29	10.9	4.55

Table 1 (continued)

LocID	Latitude (degrees)	Longitude (degrees)	K-40 (Bq/kg)	Unct ±	U-238 (Bq/kg)	Unct ±	Th-232 (Bq/kg)	Unct ±
54	18.08103	−76.7968	413.72	21.91	52.583	7.547	28.164	3.756
55	18.27376	−76.7641	350.18	23.95	Below MDA	N/A	12.345	4.137
56	18.0356	−76.7153	551.34	22.05	36.64	7.91	14.37	3.67
57	18.2388	−76.6653	301.45	24.57	60.84	9.46	14.72	4.34
58	18.02908	−76.6584	434.44	30.97	37.509	11.041	27.116	5.597
59	18.0347	−76.6201	134.04	16.97	Below MDA	N/A	8.27	3.09
60	18.04815	−76.614	561.25	24.94	33.76	9.21	50.13	4.86
61	18.20279	−76.5667	225.8	18.64	10.277	6.672	18.971	3.702
62	17.87887	−76.5	504.31	31.18	31.84	11.61	14.54	5.52
63	18.184	−76.4646	249.74	31.01	14.084	10.482	25.916	5.769
64	18.07902	−76.4252	450.83	29.07	59.231	11.083	12.669	5.024
65	17.89	−76.4239	249.1	21.83	Below MDA	N/A	14.924	3.919
66	18.16392	−76.3565	286.21	32.35	307.06	13.46	25.62	5.75
67	18.00705	−76.2653	224.28	34.24	173.19	13.22	45.29	6.34

on the Effects of Atomic Radiation (UNSCEAR). The annual gonadal dose equivalent due to the specific activities of radium-226 (Ra-226), thorium-232 (Th-232) and potassium-40 (K-40) is defined in Eq. 4 (Arafa 2004). The world average in soils is 300 μSv/year (Zaidi et al. 1999).

$$\mathrm{AGDE}\left(\frac{\mu\mathrm{Sv}}{\mathrm{year}}\right) = 3.09\,A_{\mathrm{Ra}} + 4.18\,A_{\mathrm{Th}} + 0.314\,A_{\mathrm{K40}} \quad (4)$$

The AGDE index was selected for the following two reasons: (a) it includes the three major primordial radionuclides (uranium, thorium and potassium) and dose equivalent and (b) it measures radiation and organ/tissue-specific damage in humans. In this case, the gonads of human were of particular interest as its tissue weighting factor of 0.20 is the highest in the body when compared with values of 0.12 (for the red marrow, colon, lung and stomach), 0.05 (for the bladder, breasts, liver and oesophagus) and 0.01 (for the skin and bone surface) (Eckerman et al. 2011).

Sample collection method

The application of a random systematic sampling technique resulted in Jamaica being divided into 50 square grids with a maximum sampling density of 225 m^2 per sample. A location within the grid was selected using a random generator which generated two numbers corresponding to a location within the grid. At least one representative soil sample (of minimum five subsamples taken from an area 20 m×20 m) was then collected from each location resulting in a total of 66 soil samples. The samples taken were restricted to the 0–10-cm section of the soil after all living vegetation was removed. The collected soil samples were sieved using a 2-mm sieve, dried at 60 °C for approximately 18 h and stored in a sealed cylindrical container in a cool dark area for a minimum of thirty days. This storage period, prior to gamma measurement, was chosen to ensure secular equilibrium between uranium-238 and its progenies.

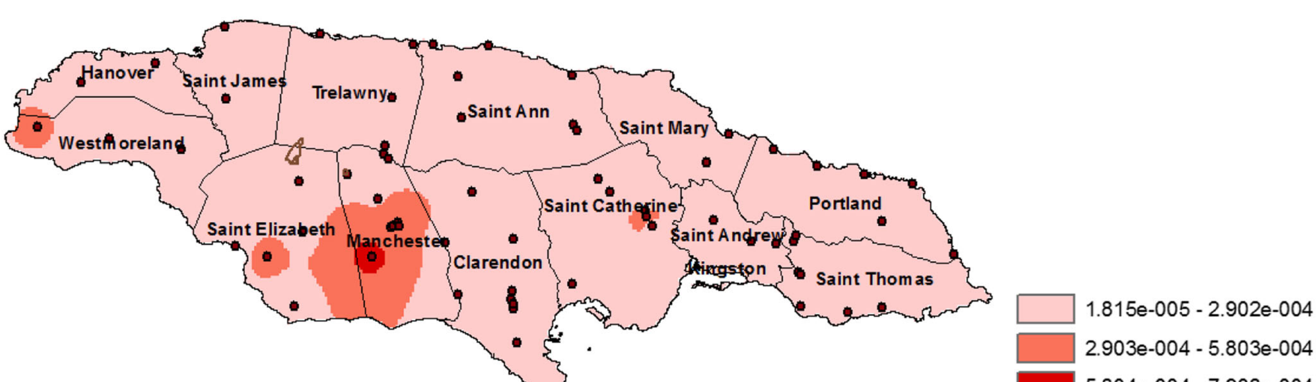

Fig. 2 Map of excess lifetime cancer risk (ELCR) for Jamaica. *Areas in lightest red* are within the world mean value of 2.9×10^{-4}. Locations are shown as *dots*

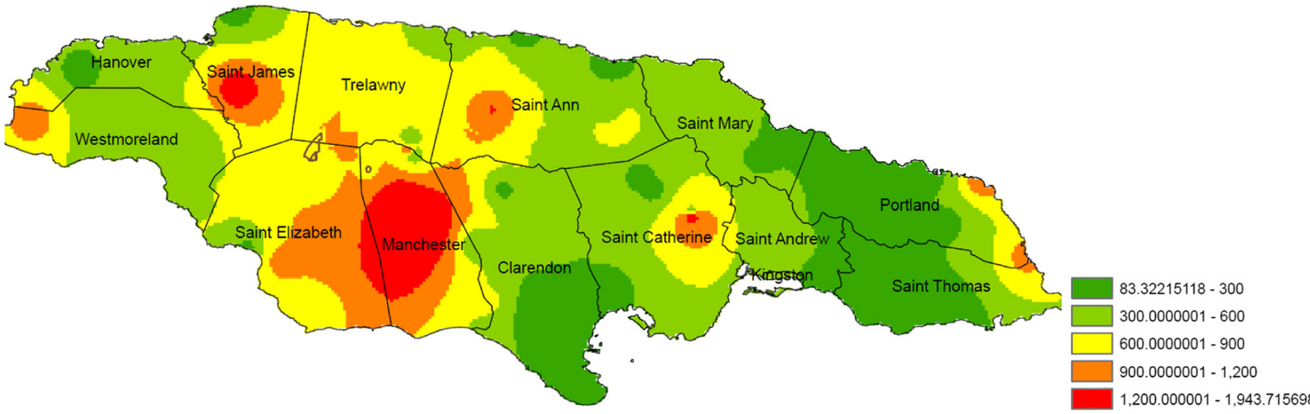

Fig. 3 Map of annual gonadal dose equivalent (AGDE) for Jamaica. *Areas in darkest green* are within the world mean value of 300 μSv/year. Locations are the same dots in Fig. 2

Spectrometry

The detector used in this research was a Canberra 3825 HPGe detector (absolute efficiency=27.61 %, measured, and 28.15 %, ISOCS value). This detector has an active area of 38 cm^2 and active diameter of 71 mm and was cryogenically cooled by liquid nitrogen in a vertical dipstick type 7500SL 30-l Dewar throughout the measurement process. The detector and samples were enclosed in a 950-kg Model 747E 10-cm-thick lead shield with graded 1-mm tin and 1.6-mm copper liner to reduce interference from lead x-rays, cosmic and background radiation during counting, which reduces counting time and improves the lower levels of detection. The floor of the shield had a 12.1-cm hole to facilitate the cryostat, and the shield itself had a 9.5-mm-thick low carbon steel. Soil and background samples were counted in lead enclosure for approximately 24 h using Genie 2000 software for spectrum acquisition. The entire detector and samples were enclosed in a lead shield to reduce the background radiation. Soil and background samples were counted in lead enclosure for approximately 24 h using Genie 2000 software for spectrum acquisition. The data for each sample were entered into a Microsoft Excel spreadsheet for further analysis. SPECTRW software was used for gamma analysis of the spectrum for each sample. A special gamma analytical method was used throughout the research to ensure that the reported values were as accurate as possible. This method involved the use of several software applications including Canberra's LabSOCS and Genie 2000 for absolute efficiency measurements and spectra counting, respectively, SPECTRW for peak analysis, EFTRAN for cascade summing correction and Sigma Plot 10.0 for both curve fitting algorithm and generation of fitting parameters.

Quality assurance

The method suggested by the equipment manufacturer (Canberra) was adopted for quality assurance during the counting process. Specific counting parameters were monitored and documented following the analysis of the radioactive source Model EU-NA-S installed in the Model ISOXSRCE Check Source Fixture which ensured a consistent geometry. This source contains Eu-155 (86.5 and 105.3 keV) and Na-22 (511 and 1275 keV); each nuclide has a 1 microcurie initial activity. On the front and side orientation position, the source is located at 10 cm above and beside the detector's end-cap. Because it was deemed impractical to move the detector from the lead shield each time the QA measurements were being done, the 86.5-keV Eu-155 peak was discarded from the analysis due to possible interference from lead X-

Table 2 Comparison by geology of the AGDE index (μSv/year) in Jamaica

	AGDE mean	Standard error	Median	Range	Standard deviation
Alluvium	370.09	60.41	252.35	130.73–971.97	249.08
Costal group	383.24	120.30	201.60	96.11–1143.36	380.43
Cretaceous	390.22	120.92	272.83	171.63–1440.73	382.40
Wagwater	204.72	70.20	240.44	69.28–304.47	121.59
White limestone	855.44	110.37	828.99	129.27–2018.25	529.33
Yellow limestone	1078.62	423.36	1210.47	288.34–1737.05	733.29
Non-limestone	366.69	48.88	252.02	69.28–1440.73	309.18
Limestone	881.19	106.49	863.84	129.27–2018.25	543.02

rays at 87.15 keV. A counting time of 5 min was employed to ensure a 1 to 2 % relative precision in the 1275-keV energy peak (Canberra 2013). In order to ensure validity and reproducibility of the spectrometric process, it was very important that the engineering specifications of the detector and the elemental concentration of the certified reference material used in Monte Carlo and absolute methods to determine the absolute efficiency, respectively, were taken into account (Miller and Voutchkov 2013a, 2013b). In this study, LabSOCS (Laboratory Sourceless Object Counting System), a mathematical method from Canberra, was used to determine a dual absolute efficiency reference curve without using a reference material. The reference curve was determined for each sample. The nuclear analysis technique employed a dual efficiency curve for the cylindrical container in contact with the face of the Canberra 3825 HPGe detector; the expressions are shown in Eq. 5. The resulting equations (for the range before and after 100 keV, respectively; see Eq. 5: dual efficiency curve for the analytical process) increased the accuracy of the spectrometry results.

$$\begin{aligned} \ln(\mathrm{Eff}) &= -38.01^* + 22.38\ln(E) - 4.642\ln(E)^2 + 0.3185\ln(E)^3 \\ \ln(\mathrm{Eff}) &= -110.8^* + 76.3\ln(E) - 20.35\ln(E)^2 + 2.56\ln(E)^3 - 0.15\ln(E)^4 + 3.214{*}10^{-3}\ln(E)^4 \end{aligned} \quad (5)$$

Minimum detection limits

Genie 2000 Nuclide MDA Report was run to generate the minimum detectable activity (MDA) for the radionuclides under investigation in this study. This report was quite useful as it showed nuclides identified during the nuclide identification process, the energies at which they were found, nuclides that required coincidence correction and nuclides whose energy were not found in the spectrum. The MDA (in Bq/kg) for the radionuclides of interest were as follows: K-40 (6.24), Tl-208 (0.889), Bi-212 (7.20), Bi-214 (1.59), Pb-214 (1.49), Ra-226 (1.16), Pa-234 (2.4), Th-234 (5.8) and U (0.706).

Results

Table 1 summarizes the values of the radionuclides measured in this study. In some instances, the specific activities were below the MDA of the detection system. Figures 2 and 3 show the spatial distribution of the excess lifetime cancer risk (ELCR) and the annual gonadal dose equivalent (AGDE) indices, respectively, in Jamaica using the inverse distance weighting (IDW) interpolation method in ArcGIS 10.1. The AGDE index values for the different soil geology in Jamaica are presented in Table 2. The values were derived by applying Eq. 4 to the entries in Table 1. Table 3 shows the results of the Spearman's correlation analysis of the AGDE index with selected parameters related with the sampling location. The highest correlation (0.51) was with the reclassified geology.

Table 3 Correlation of AGDE index with selected parameters of the sampling location

Parameter	Spearman correlation with AGDE
Soil	0.43
Height of soil location	0.41
Longitude of soil location	−0.42
Geology	0.43
Reclassified geology	0.51

Discussion

In this study, the ELCR and the AGDE radiation indices were used to infer the radiation risk to the residents of Jamaica from exposure to soil-resident naturally occurring radiative material (NORM) in bauxitic soils or any other underlying soil geology. In Jamaica, the bauxitic soils are mainly under laid by limestone rocks as shown in Fig. 1. The discussion of the results will cover the analysis of these two indices.

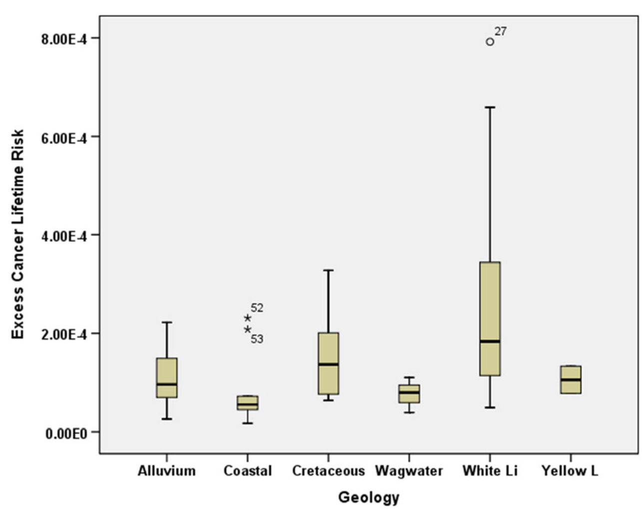

Fig. 4 Distribution of excess lifetime cancer risk index by geology in Jamaica

The excess lifetime cancer risk

The results of this study indicated that in Jamaica, the ELCR index ranged from 0.16×10^{-5} to 7.92×10^{-4} with a mean value of 1.63×10^{-4}. The world mean value for this index is 2.9×10^{-4} (Taskin et al. 2009). The percentile rank of the world mean of this index in the Jamaican sample was 0.84. This indicated that 84 % of the island exhibited a value below the world mean value of the ELCR. The 95 percentile value of the Jamaican distribution was 4.9×10^{-4}. For this index, the statistical one-sample t test indicated that the mean value of the Jamaican distribution was statistically significantly lower than the world mean value (t (65)=−6.995, $p<0.001$; Fig. 4). As shown in Fig. 2, although the distribution of the ELCR index did not exhibit any special geographic distribution pattern, it was noticeably higher over the areas bordering the parishes of St. Elizabeth and Manchester. Previous studies have shown that this area is characterized by elevated levels (with respect to international means) of uranium U-238 and thorium Th-232 in the soils and covered by bauxitic soils (Miller and Voutchkov 2014). The results of the ELCR analysis support the hypothesis of elevated risk levels based on the bauxitic nature of the soil environment in Jamaica. The AGDE index was next analysed to determine how both indices concurred.

The annual gonadal dose equivalent index

The analysis of the AGDE index showed that the highest values were found at the southern parishes of Manchester and St. Elizabeth which coincided with areas where the aluminium content of the soil exceeded 15 % in elemental concentration. This higher dose rate exposure to the gonads was due mainly to gamma radiation from uranium-enriched soils in the bauxitic areas of Manchester, the bordering parish of St. Elizabeth, and areas of St. James where the AGDE is up to five times higher than the world mean of 300 μSv/year (Kurnaz et al. 2007). The mean value of the local AGDE index (557.76 μSv/year) was determined by the one-sample t test to be statistically significantly higher than the world mean of 300 μSv/year, t (67)=4.410, $p<0.001$. The percentile rank of the world mean in the samples was 0.47, which implied that 53 % of the samples had values exceeding the world mean. The spatial distribution of this index in Fig. 3 suggested that the areas of southern Clarendon (on the south coast) and most of the eastern sections of the island had values within the world mean. Examination of Table 2 suggested that only the Wagwater geology exhibited a mean value lower than the world mean value of the AGDE index. The distribution of this index is depicted in the box-and-whisker plot in Fig. 5. The Kolmogorov-Smirnov statistical test for normality indicated that the AGDE index was non-parametric in distribution. Since the data were not normal, the non-parametric Kruskal-Wallis test was used which showed that the differences between AGDE index and the geology distribution were significant (H (5)=18.050, $p=0.003$). The last two row entries in Table 2 correspond to a reclassification of the geology as either limestone or non-limestone. A Tukey post-hoc test revealed that the only significant differences for the AGDE index were between the alluvium (370.09±60.41, $p=0.09$) compared to the white limestone group (1078.62±423.36). A visual inspection of the median values in Fig. 5 along with the results of the Mann-Whitney test for pairwise comparison suggested that the underlying soil geology may be classified as limestone and non-limestone from the perspective of the AGDE index. The distribution via the reclassified geology is shown in Fig. 6. The non-parametric Mann-Whitney pairwise comparison tests indicated that the AGDE index distribution was significant when this reclassified geology was introduced, U (1)=206.00, Z=−4.121, $p<0.001$.

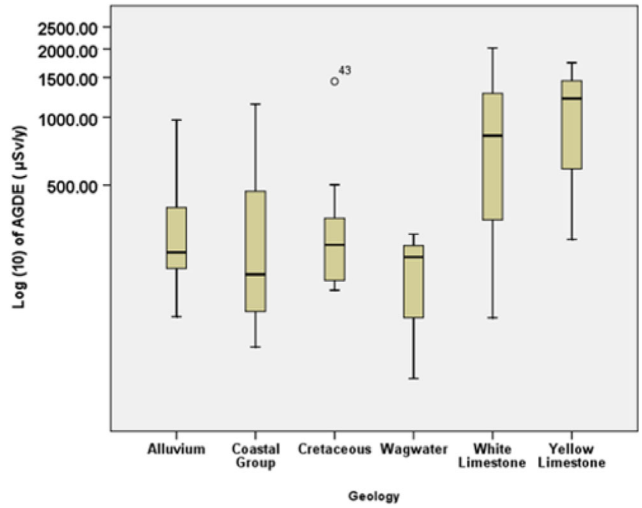

Fig. 5 Logarithmic (base 10) distribution of annual gonadal dose equivalent (AGDE) index by geology in Jamaica

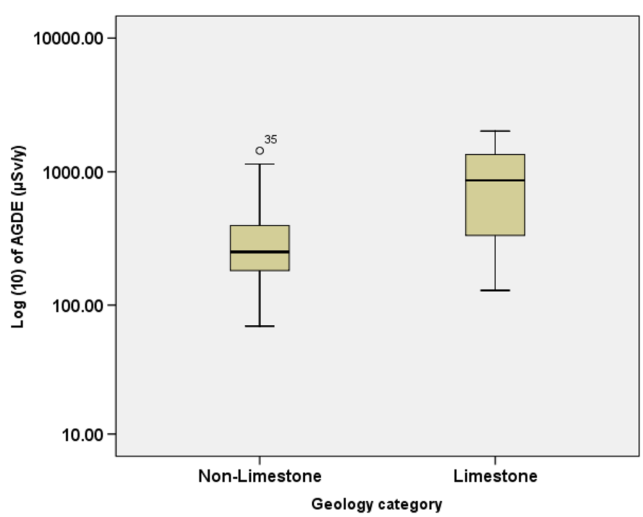

Fig. 6 Logarithmic (base 10) distribution of annual gonadal dose equivalent (AGDE) index by reclassified geology in Jamaica

A more significant correlation with geology was noted when the underlying soil geology was reclassified. As shown in the box-plot diagrams, there was a marked similarity between distributions (means and standard deviation) of the Wagwater, alluvium, coastal group and cretaceous group, which no doubt resulted in the moderate and positive correlation index of 0.43 with AGDE. The high-uranium and bauxitic areas in Jamaica suggested that these soils overlaying the white limestone geology increase the health risks from soil resident gamma radiation. The best health results (low value of AGDE) occurred where potassium K-40 concentration tended to be higher. This occurs however because thorium and uranium concentrations are very low in these areas (Miller and Voutchkov 2014). The geographical distribution of the AGDE index showed a stronger link with the bauxitic environment than the excess lifetime cancer risk index.

Conclusion

The results of this study supported the hypothesis that Jamaicans living over bauxitic soils were at a higher risk of gamma exposure from primordial radiation as assessed by the excess lifetime cancer risk (ELCR) health index. A relationship between the underlying geology and radiation exposure was not established. It should be noted that even though bauxitic soils in Jamaica have a relatively higher level of U-238 and Th-232, they also have a lower level of K-40. Since there is no consensus on the detrimental impact of low-dose radiation, analysis of the annual gonadal dose equivalent (AGDE) index was employed and inferred that the risks to the gonads are higher over the bauxitic soils in Jamaica. When the dose exposure over the underlying soil geology was investigated, the spatial and correlation analysis results suggested that the risk was not dependent on the soil geology. The increased correlation over limestone-covered soils in comparison to non-limestone geologies is probably more related to the elevated levels of U-238 in the bauxitic soil environments in Jamaica. The research purports that since the soils used in this study were surficial soils (first 10 cm), this may have accounted for the lack of a strong correlation between geology and radiation levels. Sampling closer to the underlying rocks may produce a higher correlation between gamma activity and geology. The correlation between geology and radiation levels was both quantitative and qualitative. This means that ELCR and AGDE indexes may not be the most appropriate to reveal the correlation of specific radionuclides and the soil geology. Other soil parameters like porosity, moisture and granularity can affect significantly the radiation levels. Hence, additional research is required to determine how these parameters affect the results.

Acknowledgments The authors acknowledge the contribution of Dr. Costas Kalfas, Demokritos, Greece, for the provision of the SPECTRW gamma-ray spectroscopy analytical software and the International Atomic Energy Agency (IAEA) for the outfitting of the Radioecology Lab at the University of the West Indies, Mona Campus. We also thank Professor Hanchard and Dr. Tracey Gibson from the Department of Pathology for providing cancer prevalence data and sharing their insight for a long range study of the problem.

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