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Influence of meteorological parameters on radiometric measurements: an alternative method for surveillance of environmental radiation in Brazil

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ABSTRACT

The multifactorial nature of background radiation demands a constant surveillance to be always aware of environmental radiation and radioactivity levels, and remarkable changes, to which public is exposed. The present study aimed to develop an alternative methodology of easy applicability and low cost to carry out measurements of environmental background radiation. It was used a Geiger Muller counter (GM) to measure the background radiation of Botucatu city in São Paulo state. In order to verify the lack of influence in radiation levels along the day Meteorological and Radiometric measurements were performed. The obtained data confirmed no statistically significant variations in radiometric measures during the reported period. The results were mainly presented in a map with the distribution of environmental radiation. The average value of the background radiation readings was 5.001E-09 C/kg, with an average variance of 5.295E-11 and an average standard deviation of 3.971E-08. The map was developed using Python programming language and the source code is available at: https://github.com/gabrielnarruda/lowcost-muller-map and https://github.com/gabrielnarruda/muller-map-backend. The map generated from this study will be hosted on an open access website and other GM users will be encouraged to insert their measurements and location in the map. The health of general public against deleterious effects of ionizing radiation levels can be ensured with environmental radiation surveillance. The information provided by the present study may contribute to research centers and establish a baseline for future research.

Keywords: **Background radiation, Surveillance, Radiometry, Meteorology.**

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1. INTRODUCTION

There are several types of ionizing radiation, and their characteristics vary according to the origin of production, ionization power and interaction. Ionizing radiation can have a natural or artificial origin [1,2]. Ionizing radiation called natural or background radiation, is present in the environment and in organisms, due to the radioactive materials present on Earth and to cosmic radiation on the Earth's surface and atmosphere. The contribution in the dose value is related to the location and habits of each human being. The natural origin of radiation occurs due to the presence of naturally radioactive chemical elements, with the greatest contribution coming from the decay products of Uranium and Thorium, in which the most notable are Radon and Thoron, with a small portion coming from C-14 and K-40. These radioactive families are present in rocks, water, air and soil, and can be gaseous and spread with winds, rain and air humidity [3–5].

The natural radioactivity in the air comes from the presence of the Radon and Thorium gases. The products of the decay of these elements are solid, remaining in the atmosphere by deposition in particles [6–9]. In Brazil, the materials used in civil construction are commonly rich in thorium and, therefore, it is common to have radioactivity at a higher level in conditions of poor ventilation in environments [9,10]. Water may present radioactivity due to rainwater that acquires radioactivity present in particles in the air [11], in addition, the underground and surface water deposits present radioactive substances from rocks and soils [12].

About 80% of the total dose received by human comes from Earth's natural radiation [7]. Cosmic radiation, through its secondary interactions with the Earth's surface and atmosphere, is another natural radiation agent that contributes about 15% of this total dose. This percentage can increase or decrease according to the altitude, referring to the ground, also due to the presence of attenuating elements in the air that shield this radiation [13].

Artificial sources are produced by humans and medical radiation is the major responsible for the total exposure. Other exposures come from nuclear plants, reactors and tests carried out with atomic bombs [14].

Organisms are constantly exposed to ionizing radiation from the environment, containing radioactive materials in their compositions. The human being acquires the radioactive material through the consumption of vegetables and mineral materials with which he feeds and hydrates, the most common materials being K-40, C-14 and Ra-226 [13,15].

It is important to know the radiation levels to which human beings are exposed [16]. This issue of radiological protection is the subject of scientific studies that discuss the distribution and dose values around the world. These levels of environmental radiation are, unfortunately, still poorly studied in Brazil.

It is possible to find in scientific publications several studies on the evaluation of external (environmental) dose rates on different types of surfaces [17–19]. Several methods and detectors allow the quantification and detection of radiation [20].

In this study, the measurements were performed with the Geiger Muller Counter (GM) due to the robustness of the equipment, reduced dimensions and weight, it is widely used in radiological protection services, low cost, easy handling, good response, and reproducibility for the various types of ionizing radiation, presenting applicability for environmental verification [21].

The Radiation Exposure is represented by the letter X and its SI unit is the Coulomb per kilogram (C/kg) – which replaced the former unit roentgen (R); one R equals 2.58×10^{-4} C/kg –, the radiation exposure measures the ionization from X and γ rays when producing equal charge signs in a specified volume of air divided by the mass of the air. The absorbed dose, which uses the unit gray (Gy), differs from radiation exposure as this quantity can be defined to any type of radiation that interacts with any type of matter, determining the absorbed energy in a defined volume because of the ionization. The conversion from exposure to absorbed dose is complex, some factors such radiation type, energy and material of interaction must be considered. The Geiger Muller radiation detector equipment can detect several radiation types, in our study the equipment was calibrated for radiation measure for X and γ. The GM equipment is sensible to radiation, depending on radiation type, but this equipment is not accurate. It must be considered the energetic dependency from the equipment's probe and the calibration certificate.

Based on a standardized methodology, easy to apply and low cost, it will be possible to carry out measures in several locations in the country, ensuring the verification of an ecologically balanced environment, according to the described in chapter VI, article 225 of the Constitution of the Federative Republic of Brazil (1988) [22].

Currently, the available data regarding the monitoring of the incidence of natural ionizing radiation for Brazil are scarce and mostly related to atypical locations, for commercial purposes and with a high level of radioactivity [7,23]. Such fact does not allow a satisfactory assessment of the current Brazilian scenario regarding exposure to this type of radiation. Therefore, this study sought to stablish an alternative methodology for monitoring environmental radiation using GM detectors. It was built a dataset of the levels of environmental ionizing radiation in the city of Botucatu at different geolocation points, relating them to the surface characteristics of the measurement point and the altitude of that points; analyze the correlation between the measured background radiation rates and the meteorological and radiometric measures and; develop an interactive radiation map for environmental monitoring.

2. MATERIALS AND METHODS

2.1. Development of the method of measuring the levels of environmental radiation

The device used to perform the surveillance of environment radioactivity was the Geiger Muller counter (GM). It is a model G1-E from MRA brand for α, X, γ and β ray field surveillance. The equipment has an external probe and lecture range from 0.02 mR/h to 1 R/h. The equipment had a valid calibration certificate issued by Nuclear and Energy Research Institute (IPEN) as a monitoring area detector, calibrated in Exposure (C/kg = 3876 R) using a ^{60}Co source. The equipment had not been calibrated to the ambient dose equivalent, H*(10).

Initially, two measurements were made: the first with the opening of the external probe facing downwards, perpendicular to the ground, at approximately 0.05 meters from the ground surface; the second with the opening of the external probe facing upwards, perpendicular to the ground, with 1.5 meters of ground clearance – the same ground clearance of Eppley pyrometer to measure global solar irradiance. This method was carried out to analyze if there would be any alteration in the reading of the device with the probe close to the ground, it could contain mineral materials with significant radioactivity, which could cause different background radiation readings in relation to the distances of the probe to the ground, if there were, the two readings would be noted.

After analyzing the two readings, it was established to perform 3 consecutive measurements with a 1-minute interval between them. The time interval, for each 3 consecutive readings, was 2 hours in a 24 hour period, making 36 measurements in all. All measurements obtained were carried out in favorable climatic conditions, with little or no cloud presence in the sky and without precipitation, on 07/09/2020 and 07/10/2020 at the Meteorological Station of the Faculty of Agronomic Sciences (FCA), Campus Lageado of Botucatu city.

2.2. Hourly meteorological and radiometric measurements

For the study, extraterrestrial and global solar irradiance and the values of air temperature and relative humidity were monitored, which were provided by the Botucatu Solar Radiometry Laboratory, located in the Department of Bioprocesses and Biotechnology of the Faculty of Agronomic Sciences of São Paulo State University (Unesp), Botucatu Campus (latitude 22º 54' S, longitude 48º 27' O and altitude 716 m). The experimental test was carried out for 07/09/2020 and 07/10/2020.

The city of Botucatu, State of São Paulo, is in a region where sugar cane and eucalyptus are planted. It has about 140.000 inhabitants and is surrounded by an asymmetric relief formation called Cuesta de Botucatu and by the hydrographic basins of Tietê and Paranapanema. It has few industries, and its economy is based on the provision of services. According to the Köppen climate classification, the top spot is Cwa (humid subtropical climate), with hot, humid and rainy summer and dry and mild winter. The values of temperature and relative humidity follow the astronomical variations, with maximum values of temperature and relative humidity in February (23.12 °C and 78.25% respectively) and minimum values of temperature in July (17.10 °C) and humidity relative in August (63.97%). The rainy season occurs in summer and spring, accompanied by high cloud cover. About 80% of annual precipitation occurs in this period, with a maximum in January (246.2 mm). In the winter and autumn seasons, the average rainfall is less than 100 mm monthly, with a minimum in August (36.1 mm).

The extraterrestrial solar irradiance Io was calculated by the equation:

$$I_o = 1367 * \cos\theta_Z \tag{1}$$

Where I_o is the extraterrestrial solar irradiance; 1367 W/m² is the solar constant and θ_z is the zenith angle. The global solar irradiance IG was measured by an Eppley - PSP pyranometer coupled to an automatic data acquisition system model Datalogger CR 3000 from Campbell Scientific Inc with a scan frequency of 0.2Hz. Average values were calculated every 5 minutes and stored in W/m² format. The solar irradiance values in W/m² were integrated into the hourly time partition, obtaining the irradiations (energy values) in MJ / m².

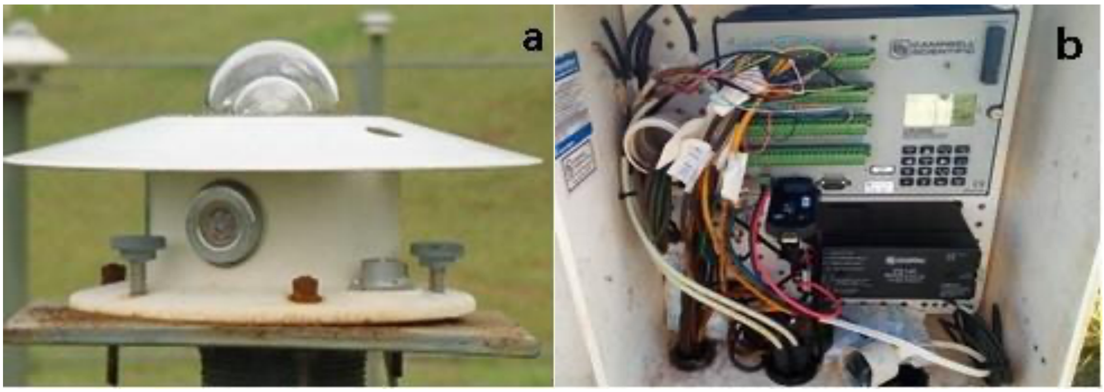

Figure 1: *Measuring instruments: a) Eppley pyranometer to measure global solar irradiance, b) CR 3000 data acquisition system - Campbell Scientific Sci.*

2.3. Dataset of the levels of environmental ionizing radiation with the altitude of its geolocation

The levels of environmental radiation were measured at 27 points in the city of Botucatu, State of São Paulo, following the methodology proposed in this work. The only exception to the methodology of the measurements carried out was the verification in the period of 24 hours in each location, that is, 3 consecutive measurements were carried out with an interval of 1 minute between them, but only at a certain time of the day. Through the geographic coordinates, it was possible to infer the altitude of each coordinate through the global positioning system (GPS) provided by Google. Table 1 shows the name and altitude of the locations where the measurements were made and used for the development of the Environmental Radiation Map. The complete database in this table contains the geographical coordinates, time, radiation index (average exposure rate, C/kg), temperature (ºC), atmospheric pressure (mmHg), relative humidity (%) and type of the surface, can be accessed through the address: bit.ly/3icIVzx.

Table 1: Radiation monitoring sites analyzed in the city of Botucatu, State of São Paulo - Measurements with GM.

Points	Location names	Alt (m)
1	Praça Rubião Júnior, Centro	835
2	Rua Dr. Costa Leite, Vila Nogueira	846
3	Rua General Teles, Centro	859
4	Praça Raul Gomes Pinheiro Machado, Centro	833
5	Avenida José Ítalo Bacchi, Jardim Aeroporto	866
6	Faculdade de Tecnologia de Botucatu (FATEC)	869
7	Hospital Estadual de Botucatu	859
8	Rod. Gastão Dal Ferra, Jardim Aeroporto (Parque Tecnológico de Botucatu)	873
9	Avenida Demétria, Jardim Alvorada	869
10	Chácara de Recreio, Jardim Alvorada (Véu da Noiva)	823
11	Rua Amando de Barros, Parque São Domingos	823
12	Rua João Passos, Centro	802
13	Rua Marechal Deodoro, Centro	815
14	Ginásio Municipal Governador Mário Covas	853
15	Avenida Paula Vieira, Vila Maria	772
16	Estação Ferroviária de Botucatu	783
17	Rua Dr. José Barbosa de Barros, Jardim Paraíso (Museu do Café)	784
18	Rua Augusto Fontana, Jardim Paraíso	757
19	Avenida Camilo Mazoni, Jardim Paraíso	833
20	Praça Cavalheiro Virgílio Lunardi, Vila dos Lavradores	817
21	Avenida Dr. Vital Brasil, Jardim Bom Pastor	822
22	Biblioteca do Instituto de Biociências de Botucatu, Rubião Júnior	891
23	Central de aulas do Instituto de Biociências de Botucatu, Rubião Júnior	900
24	Mirante Igreja de Rubião Júnior	908
25	Departamento de Dermatologia e Radioterapia da FMB	892
26	Faculdade de Medicina Veterinária e Zootecnia	887
27	Centro de Isótopos Estáveis Prof. Dr. Carlos Ducatti	898

Alt = location altitude (meters).

2.4. Development of the environmental radiation map

An interactive map was developed using Python programming language, using the open source frameworks Dash (https://dash.plotly.com/) and Flask (https://flask.palletsprojects.com/en/1.1.x/), to show the Radiation Index (C/kg/h), Altitude (m) and Type of Surface Information for each of the 27 points.

3. RESULTS AND DISCUSSION

Background radiation measurements using the GM detector were performed every 2 hours, over a period of 24 consecutive hours. This procedure aimed to analyze whether there would be a change in exposure values due to variations in temperature and relative humidity, presence and absence of sunlight at different intensity and time of day. As the equipment display the unit in mR/h it was used the conversion to Coulomb/kilogram per hour. Table 2 shows the days and times when the 3 consecutive measurements were made, as well as the mean, variance and standard deviation.

Table 2: Background radiation readings with the GM

		Reading			Average
Day	**Hour**	**1st C/kg**	**2nd C/kg**	**3rd C/kg**	**C/kg**
09/07/2020	12:30	2.35E-09	5.001E-09	5.001E-09	4.412E-09
09/07/2020	14:30	5.001E-09	5.001E-09	5.001E-09	5.001E-09
09/07/2020	16:30	5.001E-09	5.001E-09	5.001E-09	5.001E-09
09/07/2020	18:30	5.001E-09	5.001E-09	5.001E-09	5.001E-09
09/07/2020	20:30	5.001E-09	5.001E-09	5.001E-09	5.001E-09
09/07/2020	22:30	5.001E-09	5.001E-09	5.001E-09	5.001E-09
10/07/2020	00:30	5.001E-09	5.001E-09	5.001E-09	5.001E-09
10/07/2020	02:30	5.001E-09	5.001E-09	5.001E-09	5.001E-09
10/07/2020	04:30	5.001E-09	5.001E-09	5.001E-09	5.001E-09
10/07/2020	06:30	5.001E-09	5.001E-09	5.001E-09	4.412E-09
10/07/2020	08:30	5.001E-09	5.001E-09	5.001E-09	5.001E-09
10/07/2020	10:30	5.001E-09	5.001E-09	5.001E-09	5.001E-09
Average		4.795E-09	5.001E-09	5.001E-09	4.912E-09
Variance		1.986E-14	0.00	0.00	1.783E-15
Standard deviation		7.648E-10	0.00	0.00	2.289E-10

The collected measurements show an overall average of 5.001E-09 C/kg, with a variance of 5.295E-11 and standard deviation of 3.971E-08. The data do not show significant statistical variations during the 24 hours of reading, pointing to be a positive indication that the methodology applied in the collection of the points of the map is efficient and reliable. It is important to highlight the two measurements carried out, one with the probe close to the surface of the site, which may be grass, earth, sand, concrete, asphalt, water, among others, and the other with the probe at approximately 1.5 meters from the same surface, as described in the methodology. Thus, it was possible to analyze whether there would be an influence on the radiation exposure rate with the proximity of the probe to the ground, due to the Law of the inverse of the square of the distance, which could contain mineral materials with significant radioactivity to the detection of the device. In Figure 2 it is possible to verify that, statistically, there was no significant variation in the mean of the measurements performed during the 24 hours.

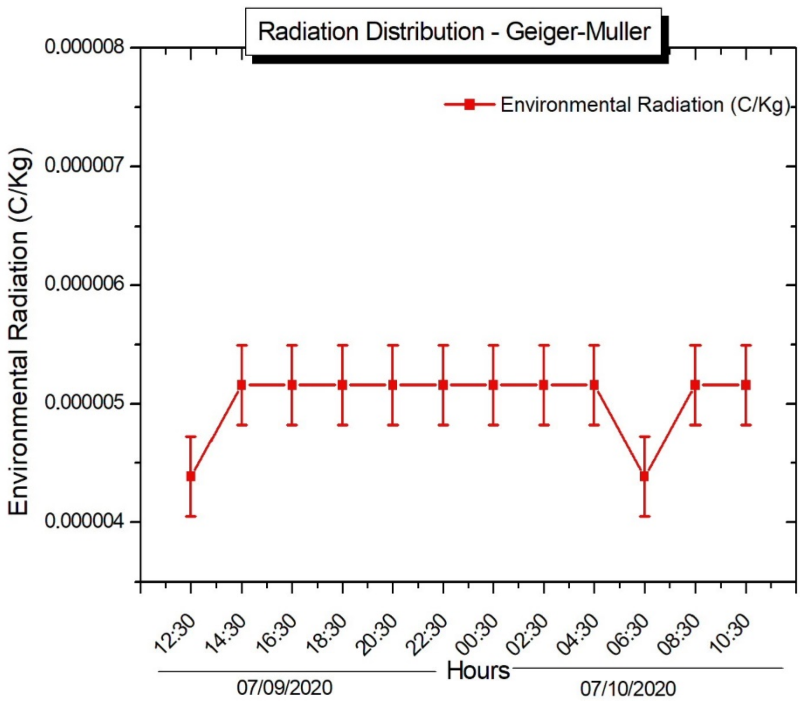

Figure 2: *Reading background radiation measurements x time.*

Concomitant with the background radiation measurements, during the 24 hours, the extraterrestrial (MJ / m²) and Global (MJ / m²) solar irradiations were monitored in a two-day time interval to verify if these two solar variables have influence on the values of environmental radiation from the same location. Figure 3 shows the hourly solar extraterrestrial and global radiation for the days 07/09/2020 and 07/10/2020. In order to verify the influence of the binomial solar radiation-atmosphere on the values of environmental radiation, only days with open sky conditions were selected, since cloudiness is a dynamic and complex event that could introduce uncertainties in the study.

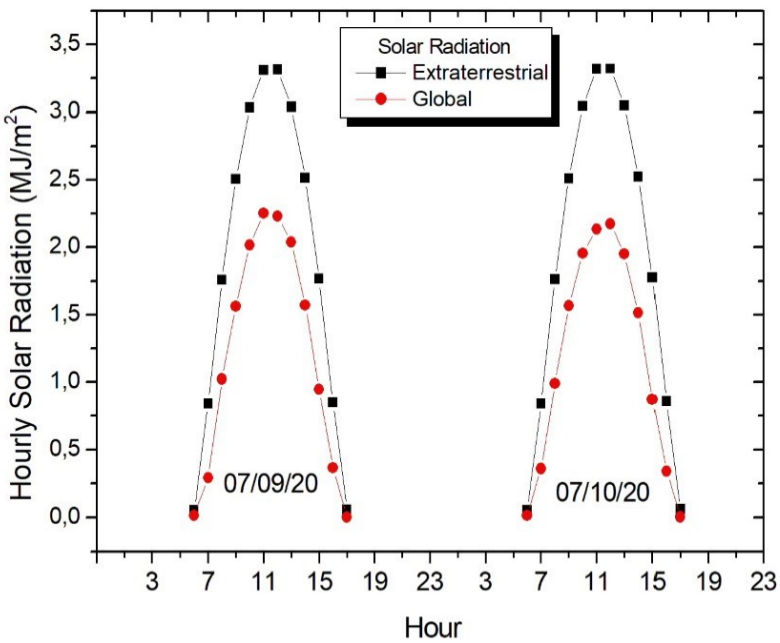

Figure 3: *Radiometric measurements. Extraterrestrial and Global solar radiation for days 07/09/2020 and 07/10/2020.*

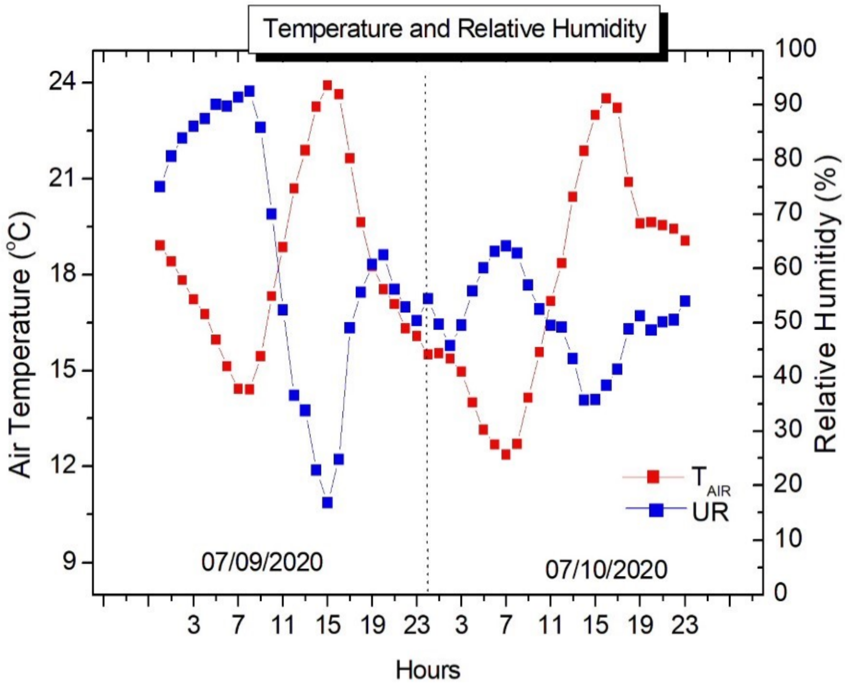

Figure 4: *Meteorological measurements. Air temperature and relative humidity for 07/09/2020 and 07/10/2020.*

Comparing the global solar irradiation in relation to the extraterrestrial irradiation, it is observed that attenuation occurs due to the difference between the extraterrestrial and global irradiations, which are due exclusively to atmospheric constituents such as aerosols, gases and water vapor. There are no abrupt attenuations due to cloudiness. The daily values of extraterrestrial and global irradiations were 23.06 MJ / m² and 14.32 MJ / m² for 07/09/2020 and 23.12 MJ / m² and 13.88 MJ / m² for 07/10/2020, respectively. In the absence of cloudiness, the attenuations of global solar radiation are caused only by atmospheric gases, aerosols and water vapor present in the atmosphere, as can be seen by the uniformity of the points on the global irradiation distribution curve over the hours. Figure 4 shows the values of temperature and relative humidity for the two days used in the study.

The temperature distribution over the two days was similar, with a minimum of around 14 ºC at 6 am and a maximum of around 24 ºC at 3 pm for both days. It is noted, by the relative humidity, that the two days are dry days with low relative humidity, showing low contribution of water vapor in the attenuation of the values of the solar radiation incident on the surface. The two days chosen were from the winter season which, in Botucatu, State of São Paulo, presents a cold and dry climate for this season.

Once the meteorological variables of the environment of the study were characterized, the global solar irradiation and the environmental radiation were correlated as shown in Figure 5.

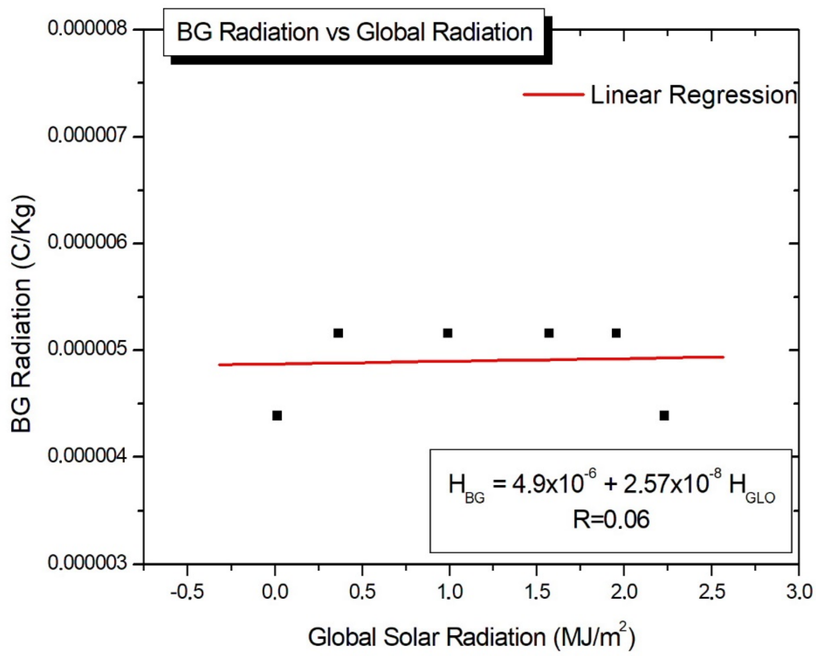

Figure 5: *Environmental Radiation due to Global Solar Irradiation.*

Angular coefficient close to zero (2.57 x 10^{-8}) shows that the values of environmental radiation do not vary depending on the values of global solar radiation. Therefore, there is no significant correlation between the values of environmental radiation and global solar radiation, also verified by the low value of the correlation coefficient (R = 0.06). Thus, it is concluded that the measurement of environmental radiation can be performed at any time, since there is no interference from solar radiation.

Measurements collected at the 27 points in the city of Botucatu, State of São Paulo, did not include different readings regarding the two measurements taken to check for the presence of mineral materials with significant radioactivity in the soil, which may present different measurements according to the distance from the probe soil, if there were both readings, they would be annotated and presented on the map, which could lead to a more in-depth survey of the soil at that specific point. It was not established a specific time for the environmental radiation measurements to be carried out in the 27 points scored on the map, because according to Figures 2 and 5 there would be no significant difference in the measurements in relation to the time of day of reading.

The interactive map (Figure 6) shows the Radiation Index (Exposure: C/kg), Altitude (m) and Type of Surface information for each of the 27 measured points can be easily expanded to cover other cities and regions in Brazil.

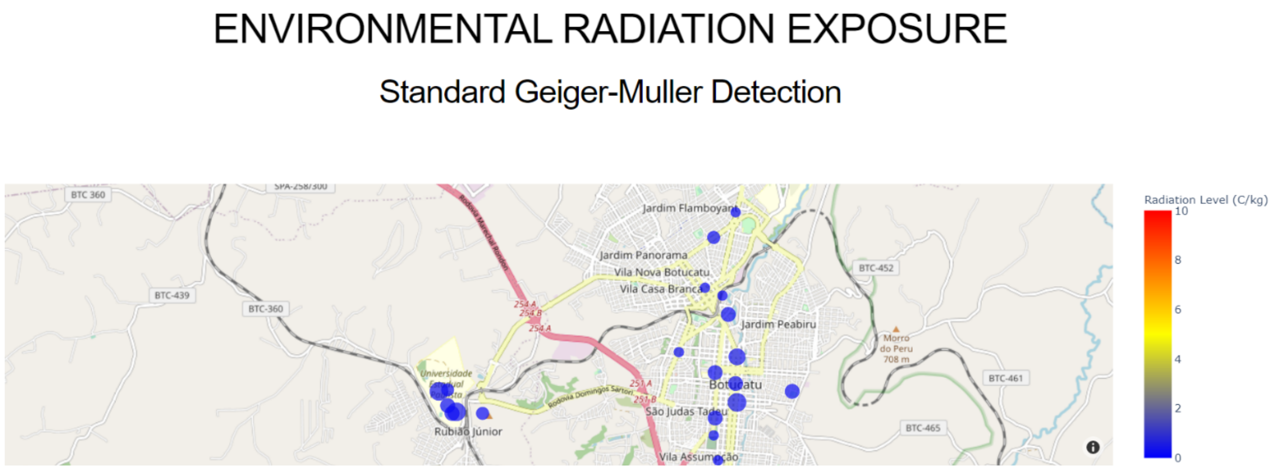

Figure 6: *Map with the measured Environmental Radiation points.*

Collected coordinates are displayed on the central map (1). Each of the points indicated on the display has a color and size proportional to the level of radiation at the normalized point of the total data set. The color scale ranges from blue (lowest value) to red (highest value). The colors may be seen on the intensity scale (2) on the right.

When hovering the mouse cursor over a point of interest, a window appears showing information about the local name, radiation level, latitude-longitude coordinates and the user who registered the information, as shown in Figure 7.

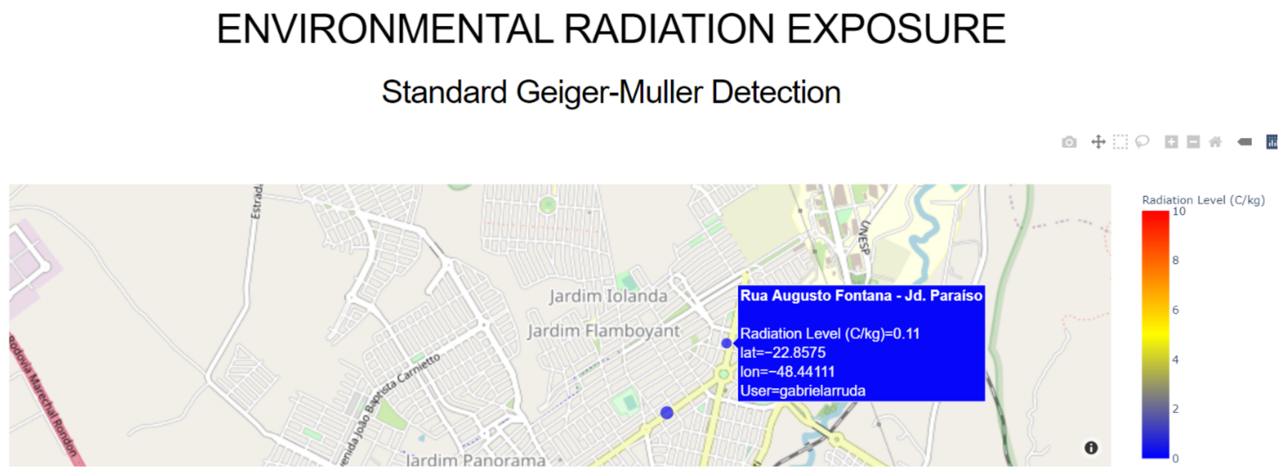

Figure 7: *Information on map points.*

4. CONCLUSION

The results corroborate the non-dependence of radiation measures and meteorological conditions. The levels of ionizing radiation for surveillance of environmental radiation in Botucatu clearly are the first scale of the detector, which means that either the levels are lower than the equipment can read or it is a value closer the initial scale value, either way this data will serve as a base line for future measurements. The alternative methodology used in the present study to analyze the level of environmental radiation at specific points proved to be simple to apply for any GM owner. This allows the reproduction of this method by any professional or student who knows how to manipulate a GM in order to perform the measurements, and thus contribute to the increase of monitored sites, helping to inform the population and local health authorities about environmental radiation exposure levels. It is essential that GM equipment has a valid calibration and the same methodology as this work to be used.

Despite the well-known limitations of the GM regarding quantification of ionization and the type of radiation dependence, we strongly believe that establishing a baseline for measurements will collaborate with future Brazilian nuclear research, reaching locations where those type of measurements have never been performed. Also, the map is a tool that provides visual data, this is useful to show the location of the measurement, information of the environment and for future consultations of the data.

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