Environmental gamma radiation in municipalities of Eastern of São Paulo State, Brazil

Rodrigo O. Bastos
Department of Physics (CCE)
State University of Londrina – UEL
bastosrodrigoo@yahoo.com.br

Elisabete M. Pascholati
Institute of Geosciences
University of Campinas – UNICAMP
paschol@ige.unicamp.br

ABSTRACT *Aerial gamma spectrometric data have been processed aiming to estimate outdoor gamma radiation dose for an area of about 11,500 Km^2, located in the eastern portion of São Paulo State, Brazil. The study comprises the Campinas city and surrounding areas, including over fifty other municipalities with a total population of about 3.5 million people. The reliability of these processed data have been evaluated by comparing the dose estimates obtained from the aerial gamma spectrometric data for the Itu Intrusive Suite with available estimates yielded from ground surveys. Between the estimates, this assessment showed a difference of about 27%, probably due to radioelements losses during pedogenesis and attenuation due to soil moisture and vegetation cover. The municipalities situated over sedimentary rocks of Paraná Basin presented lower averages while the highest ones were found in municipalities where part of the area covers granite intrusive suites. Average radiation dose per municipality have been compiled for the fifty municipalities approached in this research. Averages varied from 39 $nGy.h^{-1}$ in Engenheiro Coelho to 109 $nGy.h^{-1}$, in Votorantim. Median values were estimated for Campinas, Itu and Paulínia (68 $nGy.h^{-1}$, 65 $nGy.h^{-1}$ e 60 $nGy.h^{-1}$, respectively). The major contributor to the absorbed dose in all municipalities was the ^{232}Th series. The population-weighted average radiation dose yielded for the fifty municipalities was found to be 64 $nGy.h^{-1}$, which is slightly higher than the world's average (57 $nGy.\ h^{-1}$). The estimated radiation doses presented in this study are similar to published data for areas comprising analogous rocks and likewise, these gamma-ray dose levels show no indication of health hazards for human being.*

KEYWORDS *environmental radiation, Brazil, Medical Geology, Nuclear Geophysics*

Introduction

Most spatial variability of gamma radiation or radon concentration is consequence of geological factors. When this causes public health hazard, the problem may be defined as a medical geology problem. Medical geology, as defined by Selinus (2004), is the science that deals with the relationship between natural geological factors and health in men and animals, and urges to understand the influence of ordinary environmental factors on the geographical distribution of such health problems.

Geology and gamma radiation

The most important sources that contribute to the radiation absorbed by human populations occurs in the natural environment: cosmic rays; radioactive isotopes present in human body; and ^{40}K, ^{238}U, and ^{232}Th of rocks and soils that form the Earth's crust. This paper deals with the latter as source of gamma radiation that yields the major contrasts of dose values in a regional scale.

Most radiation that reaches the atmosphere comes from the decay of radioactive elements located to a depth of about 30 cm (Rybach 1994), all rocks and soils being radioactive in different levels. Observing several results of researches on soil and lithologic association with radioelements concentration (Dickson and Scott 1997, Pascholati *et al.* 1997, Ramli 1997, Nageswara Rao *et al.* 1996, Grasty *et al.* 1984) some aspects of the distribution of U, Th and K on the surface may be verified.

Although the same kind of rock presents wide intervals of concentration values, some tendencies can be observed. Usually, the average quantity of radioactive elements in igneous rocks tends to be larger with the increase of the acidity of the rock (mafic and ultrabasic rocks are expected have smaller concentrations of Th, U and K than felsic rocks). Dickson and Scott (1997), based on data of gneissic rocks derived from granites and of amphibolites derived from dolerites, suggest that the metamorphism does not affect significantly radioelements concentration. Sedimentary rocks reflect, at least in part, the radioactive signature of their source parent rocks (arkoses have relatively higher contents than sandstones). Actually, it should be noticed that for mature sediments – those composed mostly of quartz – smaller values of concentration are expected regardless of which one has been the parent rock. Weathering of rocks and the process of pedogenesis, in general, cause losses of about 20 to 30 percent of all radioelements. Felsic rocks follow this rule well, but basic and intermediary rocks, despite the loss of K, produce soils with relatively elevated concentration of U and Th, their quantity increasing with the rock's basicity (Dickson and Scott 1997).

Gamma radiation and health hazard

It is well known that ionizing radiation produce genetic mutations and, for this reason, it is pointed out as a source of many kinds of cancer. This hypothesis is consistent with various cancer types that have strong hereditary determinants. It is generally accepted that carcinogenesis, the process that transforms a normal cell into a cancer cell, is multistaged. In other words, in a cell, any single event by itself is not sufficient to turn a normal cell into a cancer cell. Usually, different mutations are needed for a tumor to develop (RERF 2004).

Ionizing radiation has been targeted by different kinds of studies for its effects on live organisms. Despite some exceptions, as the adaptative response (Wolf 1992), the major known effects of radiation in human beings come from high-level expositions (Yalow 1983). Experimental results of *in vitro* biological effects due to low level exposition to radiation (even in relatively high rates) allied to researches of chronic expositions by human populations, may indicate that low rates are equally liable to cause significant damages regarding cellular death and/or chromosomal instability. This is a possible explanation for the verification of hematological alterations (probably due to problems in cells of the bone marrow) in children, years after having received a small dose for a long period (Chang *et al.* 1999).

In spite of this, there is not much evidence of harmful effects for low doses of radiation. Actually, it has ever been difficult to establish them. An estimate of precise effects remains inconclusive and the conclusions being pointed by studies of diverse nature, nonreplicable. In fact, it is known that radiation, in different doses and times of exposition can induce many responses in living beings. These responses generally are not healthy to the organism, eventually increasing the damage by some other

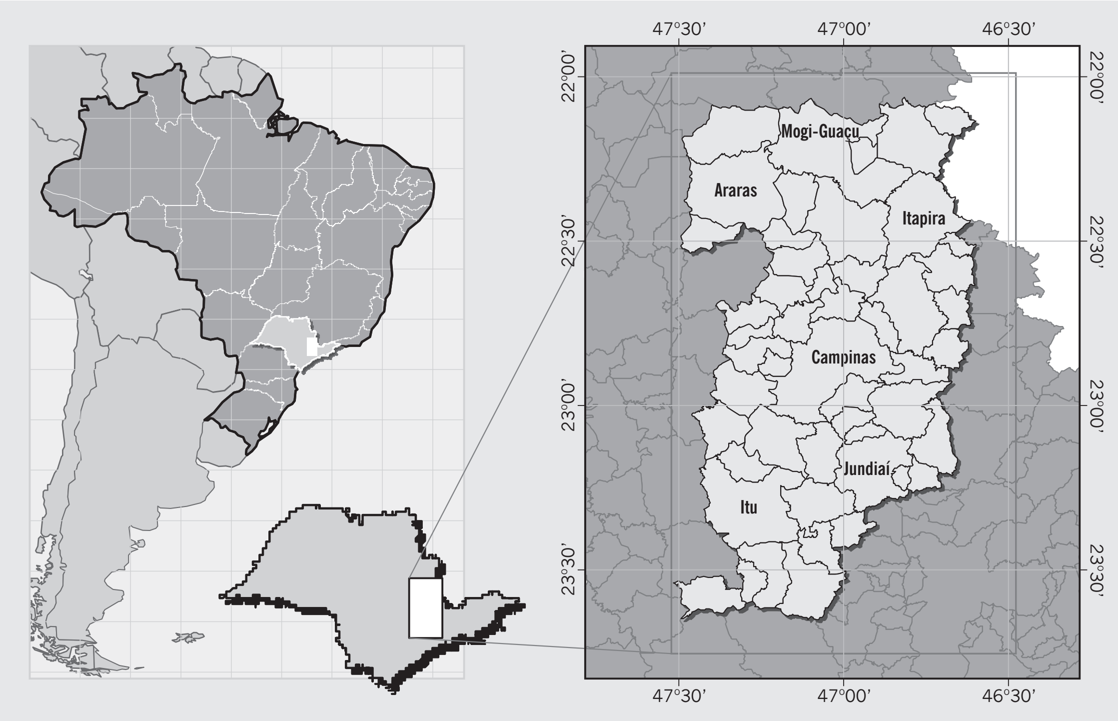

Figure 1 – Location map

risk factors that act in a similar form (i.e.) other ionizing agents.

The search for a solution to tackle this problem is motivated by the need to enunciate safety limits of radiation permitted in work places and in general environment (Mauss 1983), and to assess the possible role of ionizing radiation in the etiology of diseases which origins are still unknown. An example of this last case would be the infantile cancer (Gilman and Knox 1998, Richardson *et al.* 1995, Knox *et al.* 1988).

In this context, the need of knowing the geographical distribution of natural absorbed radiation dose arises.

Materials and methods

Aerial Data

It is possible to get information on the geology of an area by mapping the variation in the intensity of its natural radioactivity. The different classes of soils and rocks superficially located influence terrestrial or aerial gamma spectrometric data. Knowing that, the geological services of several countries, including Brazil, have conducted great gamma spectrometric surveys of widespread areas.

The original purpose of the aerial geophysical surveys conducted in Brazil by CPRM (Geological Survey of Brazil, AERO 1995) was to support geological mapping, aiming mainly mineral exploration. In this work, data from the São Paulo – Rio de Janeiro Project, carried out by the same company, were processed and analyzed, considering the municipal areas of the studied region. Envisaging an estimate of the dose absorbed by municipal populations, gamma ray spectrometry was used to calculate the concentration of radioactive elements in terrestrial environment and then the radiation dose rate in air. It enabled the generation of a map of average radiation dose per municipality.

The data is originally displayed in flight lines 1 km far from each other. Along the flight lines, point measurements are at distances of about 100 m from one another. Technical information on the survey height correction and reduction of atmospheric background and Compton Effect may be found in Anjos and Mourão (1988).

To evaluate the reliability of these processed data, results for the Itu Intrusive Suite obtained from the aerial data were compared with published values estimated from terrestrial surveys (Pascholati *et al*. 1997, Pascholati 1990).

It is also worth to stress here that, given the spatial variability of the radioactivity originated from soils and rocks, the use of aerial data in the radiation dose estimate permits a representative sampling of more widespread areas, which is really difficult for any terrestrial survey – always with a limited number of sample points. Under these terms, aerial survey reveals itself a much more appropriated method for the estimate of radiation levels.

Area delimitation

The gamma spectrometric data used here refers to the data obtained from the sub-area 6 of the São Paulo – Rio de Janeiro Project, carried out by CPRM (AERO 1995). It is delimited by the polygon that has as its vertices the following coordinates: 46º 30' and 47º 30' West longitude, 22º 00' and 23º 45' South latitude.

This area, of about 11,500 km^2, is located in the eastern portion of São Paulo State, Brazil, and comprises the Campinas city and surrounding areas, including over fifty other municipalities with a total population of about 3.5 million people (Fig. 1).

This area reveals interesting lithological differences. At northeast, the area covers the sedimentary rocks of Paraná Basin, a geological unit that, in general, presents low concentrations of radioactive elements. At southwest, there are granite intrusive suites (with known higher concentrations of ^{40}K, ^{238}U, and ^{232}Th) fitted in sequences of meta-sedimentary rocks, where lower radiometric responses are expected. The sedimentary coverage of this last portion is very restricted.

Sensitivities and radiation dose estimates

The sensitivity values (counts per unit of time per unit of element concentration) used were 4.7 cps/ppm, 7.5 cps/ppm, 62.86 cps/%, for eTh, eU and K, respectively. These values were calculated through the theoretical model developed by Amaral and Pascholati (1998).

To estimate the radiation dose, the specific activity of samples with separately 1 ppm of U, 1 ppm of Th, and 1% of K, was respectively considered as 13.0, 4.1 and 317 Bq/Kg. The dose contributions by ^{238}U (sub-series of the ^{226}Ra), ^{232}Th (all the series) and ^{40}K are respectively represented by the conversion coefficients (absorbed dose rate in the air per activity concentration) 0.440, 0.640, 0.0414 $nGy.h^{-1}/Bq.Kg^{-1}$. These coefficients were compiled from UNSCEAR (1993) and Grasty *et al.* (1984).

Results and discussion

Itu Intrusive Suite

Among the granite bodies located in the area, the Itu Intrusive Suite is the one that has its radiometric properties best studied (Pascholati *et al.* 1997, Pascholati 1990).

For this reason, the dose was calculated for the Itu Intrusive Suite using both data, terrestrial and aerial. The average dose obtained through terrestrial data is 145 $nGy.h^{-1}$ (minimum, 28 $nGy.h^{-1}$, maximum, 381 $nGy.h^{-1}$). The average dose obtained through aerial data is 106 $nGy.h^{-1}$ (minimum, 16 $nGy.h^{-1}$, maximum, 237 $nGy.h^{-1}$). The systematically smaller values (attenuation of 27%) found through aerial data is probably due to vegetation cover and soil moisture not considered in the estimate, and also to intrinsic features of the data, in which dose values represent the mean in an area that depends essentially on flight height. Besides these factors, weathering of acid rocks generally may also cause depletion of radioactive elements of about 20 to 30% (Dickson and Scott 1997). In this sense, very reasonable values were found in this study. Recent results of radionuclides specific activities on groundwater of Morungaba Granitoids, located in the same region, showed consistency with data presented here (Santos and Marques 2005, Silva and Santos 2005).

Radiation dose estimates in municipalities

Due to the need of anti-alising filter application to the interpolation processes, grids constructed by using original data do not have the same degree of spatial variation present in profiles, measured along the flight lines. Considering that, Grasty (1984) choosed to use profiles instead of grids to estimate dose for population, as they would preserve the real variations of the superficial radioactivity. Bastos and Pascholati (2001) opted to use grids, as they would reflect the regional character (not punctual) of the superficial variation of the environmental gamma radiation,

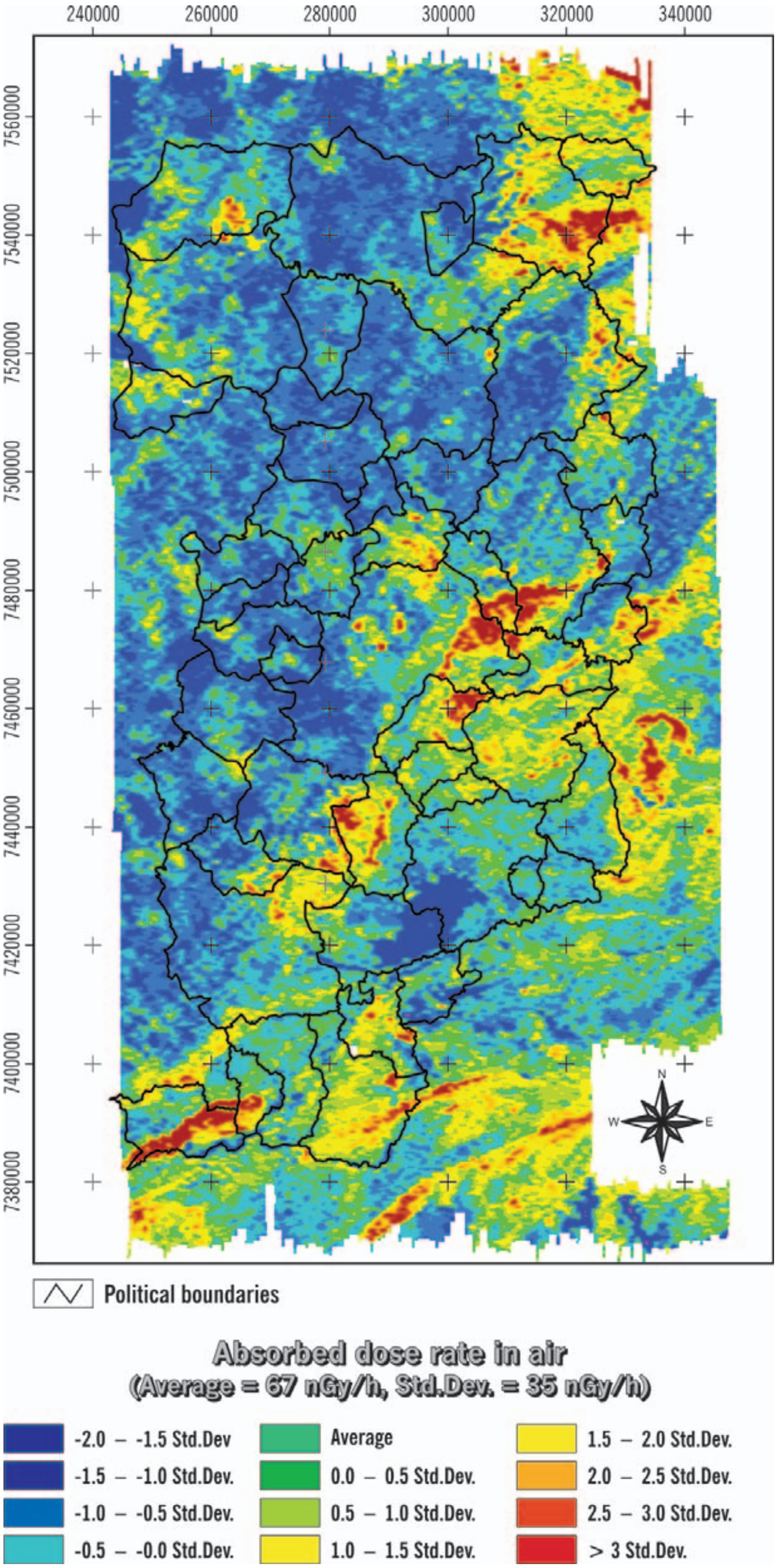

Figure 2 – Map of political limits between municipalities (IBGE 1999) of São Paulo State, which are completely within the surveyed area, over the grid map of absorbed gamma radiation dose rate in air calculated for the profiles measured along flight lines.

since the distribution of the population has the same character. This last argument should proceed if the geographical distribution of population inside municipalities boundaries is taken into account. Nevertheless, it is not the case in this work where the profiles were used.

Grasty (1984) claims that the dose values estimated by using concentrations of radioactive elements, inferred by aerial data, must be submitted to correction factors related to: the effect of vegetation cover, the variation of soil moisture along the year, and the population distribution.

In the present study, the effect of vegetation and soil moisture was not considered in the analysis. So the following values may be underestimated.

The conventional way to treat population distribution is to assume a population equally distributed in politically determined areas. This happens because the accessible population data are usually the demographic senses, which have this political division as a minimum unit of area. This approach has been used in scientific works that deal with radiation, either originated from anthropic sources (Hatch and Susser 1990) or from natural sources (Grasty *et al.* 1984, Gilman and Knox 1998, Richardson *et al.* 1995).

The Figure 2 shows a map where political limits (IBGE 1999) between

Table 1 – Average, standard deviation, and interval (minimum and maximum values) of absorbed dose rate in air for the municipalities presented in Figure 2. The contribution of each radioelement is presented. Statistics refers to profile points values that are within the municipal limits

Nº	Municipality	Number of points	Dose / nGy.h^{-1}	^{40}K / nGy.h^{-1}	^{232}Th / nGy.h^{-1}	^{238}U (sub-series of the ^{226}Ra) / nGy.h^{-1}
1	Votorantim	1853	109 ± 67 / 0 - 385	27 ± 16 / 0 - 108	65 ± 49 / 0 - 256	18 ± 15 / 0 - 93
2	Espírito Santo do Pinhal	3888	102 ± 48 / 12 - 355	31 ± 20 / 0 - 118	57 ± 31 / 4 - 242	13 ± 10 / 0 - 72
3	Valinhos	1455	99 ± 39 / 36 - 264	30 ± 17 / 0 - 94	52 ± 22 / 11 - 143	18 ± 11 / 0 - 65
4	Itupeva	2011	98 ± 42 / 8 - 278	24 ± 15 / 2 - 82	58 ± 26 / 4 - 184	16 ± 11 / 0 - 57
5	São Roque	3098	95 ± 31 / 10 - 236	25 ± 12 / 0 - 71	50 ± 26 / 1 - 142	20 ± 11 / 0 - 67
6	Morungaba	1459	95 ± 36 / 35 - 251	23 ± 15 / 0 - 85	58 ± 28 / 12 - 150	14 ± 9 / 0 - 57
7	Santo Antônio do Jardim	1069	94 ± 26 / 37 - 222	28 ± 18 / 1 - 89	56 ± 22 / 18 - 149	10 ± 8 / 0 - 41
8	Itatiba	3269	93 ± 26 / 34 - 209	19 ± 10 / 0 - 79	59 ± 21 / 15 - 167	15 ± 10 / 0 - 64
9	Pedreira	1089	92 ± 50 / 14 - 273	31 ± 14 / 3 - 81	45 ± 32 / 3 - 152	16 ± 12 / 0 - 65
10	Alumínio	859	89 ± 44 / 1 - 248	28 ± 11 / 1 - 69	47 ± 31 / 0 - 161	14 ± 11 / 0 - 70
11	Araçariguama	1455	85 ± 33 / 7 - 236	29 ± 12 / 0 - 73	37 ± 18 / 0 - 132	18 ± 12 / 0 - 67
12	Jaguariúna	1420	82 ± 36 / 6 - 271	18 ± 15 / 0 - 75	51 ± 24 / 1 - 181	14 ± 9 / 0 - 49
13	Vinhedo	818	82 ± 20 / 42 - 149	27 ± 10 / 6 - 66	41 ± 13 / 12 - 89	14 ± 8 / 0 - 61
14	Louveira	551	81 ± 21 / 34 -160	24 ± 8 / 7 - 54	44 ± 15 / 17 - 111	13 ± 8 / 0 - 45
15	Tuiuti	1279	80 ± 40 / 16 - 337	14 ± 11 / 0 - 60	54 ± 35 / 0 - 286	13 ± 8 / 0 - 46
16	Lindóia	492	76 ± 28 / 18 - 150	23 ± 12 / 2 - 65	35 ± 15 / 6 - 100	17 ± 9 / 0 - 41
17	Jarinu	2100	75 ± 26 / 21 - 191	12 ± 7 / 0 - 57	47 ± 20 / 15 - 159	15 ± 9 / 0 - 48
18	Amparo	4449	73 ± 42 / 16 - 296	23 ± 13 / 0 - 93	35 ± 26 / 0 - 166	15 ± 11 / 0 - 63
19	Mairinque	2082	72 ± 20 / 0 - 149	26 ± 12 / 0 - 92	34 ± 11 / 0 - 93	12 ± 8 / 0 - 55
20	Campinas	8007	68 ± 39 / 3 - 311	18 ± 15 / 0 - 91	38 ± 25 / 0 - 221	12 ± 8 / 0 - 58
21	Cordeirópolis	1499	66 ± 27 / 5 - 132	6 ± 4 / 0 - 19	40 ± 17 / 0 - 91	19 ± 12 / 0 - 71
22	Serra Negra	1992	65 ± 23 /19 - 219	21 ± 12 / 0 - 70	28 ± 13 / 0 - 144	16 ± 9 / 0 - 54
23	Itu	6435	65 ± 29 / 10 - 218	22 ± 14 / 0 - 87	32 ± 17 / 0 - 122	11 ± 7 / 0 - 41
24	Indaiatuba	3131	65 ± 36 / 13 - 237	13 ± 12 / 0 - 68	38 ± 24 / 2 - 167	14 ± 8 / 0 - 59
25	Leme	4053	62 ± 29 / 0 - 200	7 ± 6 / 0 - 51	39 ± 20 / 0 - 132	16 ± 11 / 0 - 65

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municipalities were superposed on a map showing the gamma radiation dose.

The Figure 3 presents a map of average radiation dose per municipality (average of profile points values that are within the municipal limits) and the Table 1, presents the results for several municipalities. The average annual dose for the fifty municipalities is 67 nGy.h^{-1}, and the population-weighted average is 64 nGy.h^{-1}. It is interesting to see that most of the absorbed dose is caused by ^{232}Th concentration. For municipalities with higher dose estimates ^{232}Th contribution to dose is followed by ^{40}K and then by ^{238}U series. Municipalities with lower dose estimates ^{232}Th contribution is followed by ^{238}U series and then by ^{40}K.

The estimate could be improved if population

Table 1 – *(continued from previous page)*

Nº	Municipality	Number of points	Dose / $nGy.h^{-1}$	^{40}K / $nGy.h^{-1}$	^{232}Th / $nGy.h^{-1}$	^{238}U (sub-series of the ^{226}Ra) / $nGy.h^{-1}$
26	Várzea Paulista	336	62 ± 12 / 36 - 95	19 ± 7 / 4 - 38	32 ± 8 / 13 - 61	12 ± 6 / 0 - 35
27	Monte Alegre do Sul	1087	62 ± 28 / 16 - 207	19 ± 12 / 0 - 67	26 ± 15 / 4 - 123	17 ± 11 / 0 - 56
28	Salto	1332	62 ± 33 / 11 - 178	14 ± 11 / 0 - 79	34 ± 21 / 0 - 115	14 ± 8 / 0 - 44
29	Campo Limpo Paulista	821	62 ± 13 / 29 - 113	17 ± 6 / 2 - 48	32 ± 9 / 9 - 74	13 ± 7 / 0 - 46
30	Paulínia	1388	60 ± 20 / 0 - 126	7 ± 5 / 0 - 35	42 ± 17 / 0 - 95	11 ± 7 / 0 - 38
31	Itapira	5190	60 ± 33 / 10 - 227	20 ± 15 / 0 - 93	27 ± 18 / 0 - 128	12 ± 8 / 0 - 53
32	Araras	6579	56 ± 25 / 1 - 200	6 ± 4 / 0 - 34	36 ± 17 / 0 - 134	14 ± 10 / 0 - 69
33	Jundiaí	4342	54 ± 23 / 1 - 120	15 ± 9 / 0 - 58	30 ± 14 / 0 - 80	9 ± 7 / 0 - 46
34	Pirapora do Bom Jesus	1131	54 ± 25 / 0 - 223	24 ± 11 / 0 - 56	24 ± 14 / 0 - 160	6 ± 6 / 0 - 38
35	Cosmópolis	1538	52 ± 19 / 2 - 121	8 ± 6 / 0 - 39	33 ± 15 / 0 - 89	11 ± 7 / 0 - 34
36	Mogi Guaçu	8192	51 ± 25 / 0 - 277	8 ± 11 / 0 - 87	32 ± 18 / 0 - 197	11 ± 7 / 0 - 41
37	Cabreúva	2596	51 ± 29 / 1 - 153	14 ± 13 / 0 - 74	28 ± 17 / 0 - 79	8 ± 7 / 0 - 33
38	Estiva Gerbi	736	49 ± 21 / 10 - 112	7 ± 6 / 0 - 36	28 ± 14 / 3 - 79	14 ± 8 / 0 - 40
39	Conchal	1877	49 ± 15 / 12 - 98	5 ± 3 / 0 - 28	33 ± 11 / 4 - 71	12 ± 7 / 0 - 39
40	Americana	1349	49 ± 22 / 0 - 121	7 ± 5 / 0 - 34	30 ± 17 / 0 - 93	11 ± 7 / 0 - 42
41	Elias Fausto	2005	47 ± 20 / 9 - 128	9 ± 5 / 0 - 33	25 ± 14 / 0 - 91	13 ± 7 / 0 - 44
42	Santo Antônio de Posse	1544	46 ± 15 / 6 - 98	8 ± 6 / 0 - 37	27 ± 12 / 2 - 68	12 ± 7 / 0 - 36
43	Moji-Mirim	5155	46 ± 16 / 11 - 181	6 ± 4 / 0 - 39	27 ± 13 / 3 - 140	13 ± 7 / 0 - 50
44	Monte Mor	2386	46 ± 20 / 9 - 128	10 ± 7 / 0 - 36	23 ± 13 / 0 - 90	12 ± 7 / 0 - 45
45	Sumaré	1507	45 ± 19 / 12 - 123	6 ± 4 / 0 - 22	28 ± 14 / 4 - 87	12 ± 7 / 0 - 44
46	Hortolândia	622	43 ± 21 / 7 - 115	6 ± 4 / 0 - 20	26 ± 15 / 0 - 81	11 ± 7 / 0 - 33
47	Nova Odessa	743	43 ± 18 / 0 - 112	6 ± 4 / 0 - 28	24 ± 13 / 0 - 84	12 ± 7 / 0 - 39
48	Holambra	664	41 ± 13 / 12 - 86	6 ± 4 / 0 - 24	25 ± 9 / 5 - 59	10 ± 6 / 0 - 28
49	Artur Nogueira	1770	40 ± 12 / 11 - 93	5 ± 4 / 0 - 23	24 ± 10 / 3 - 67	11 ± 7 / 0 - 36
50	Engenheiro Coelho	1130	39 ± 11 / 10 - 79	5 ± 4 / 0 - 23	24 ± 9 / 4 - 60	10 ± 7 / 0 - 34

data for smaller areas were available. Alternatively, a possible solution to improve the estimate would be to use the data of the senses itself and some well-known characteristics of the population dynamics to model the distribution of the population within the municipal district. Or even making use of satellite images to identify residential zones. It would be possible, then, to weight dose values of smaller areas according to their population density. That would certainly lead up to an estimate much more reliable and consistent with the mean dose of radiation received by the municipal populations.

Conclusions

As expected, municipalities situated over sedimentary rocks of the Paraná Basin have presented lower dose averages (Artur Nogueira 40 $nGy.h^{-1}$, Engenheiro Coelho 39 $nGy.h^{-1}$). The higher ones were estimated in municipalities where part of the area covers granite intrusive suites (Votorantim 109 nGy.h^{-1}, Espírito Santo do Pinhal 102 nGy.h^{-1}, Valinhos 99 nGy.h^{-1}). For this reason all of them presented high variations of dose values in their own municipal areas – the granites are fitted in meta-sediments sequences with much lower concentration of radiogenic isotopes. Median values were estimated for Campinas (68 nGy.h^{-1}), Itu (65 nGy.h^{-1}) and Paulínia (60 nGy.h^{-1}) cities. The average absorbed dose rate calculated for the fifty municipal districts was 67 nGy.h^{-1}, very near to the published values for France (68 nGy.h^{-1}) and Finland (65 nGy.h^{-1}) (UNSCEAR 1993). The population-weighted average radiation dose yielded for the fifty municipalities was found to be 64 nGy.h^{-1}, which is slightly higher than the world's average 57 nGy.h^{-1} (UNSCEAR 1993).

Most of the absorbed dose is caused by ^{232}Th concentration. For municipalities with higher dose estimates, ^{232}Th contribution to dose is followed by the ^{40}K and then by the ^{238}U series contribution. Municipalities with lower dose estimates, ^{232}Th are followed by ^{238}U and then by ^{40}K.

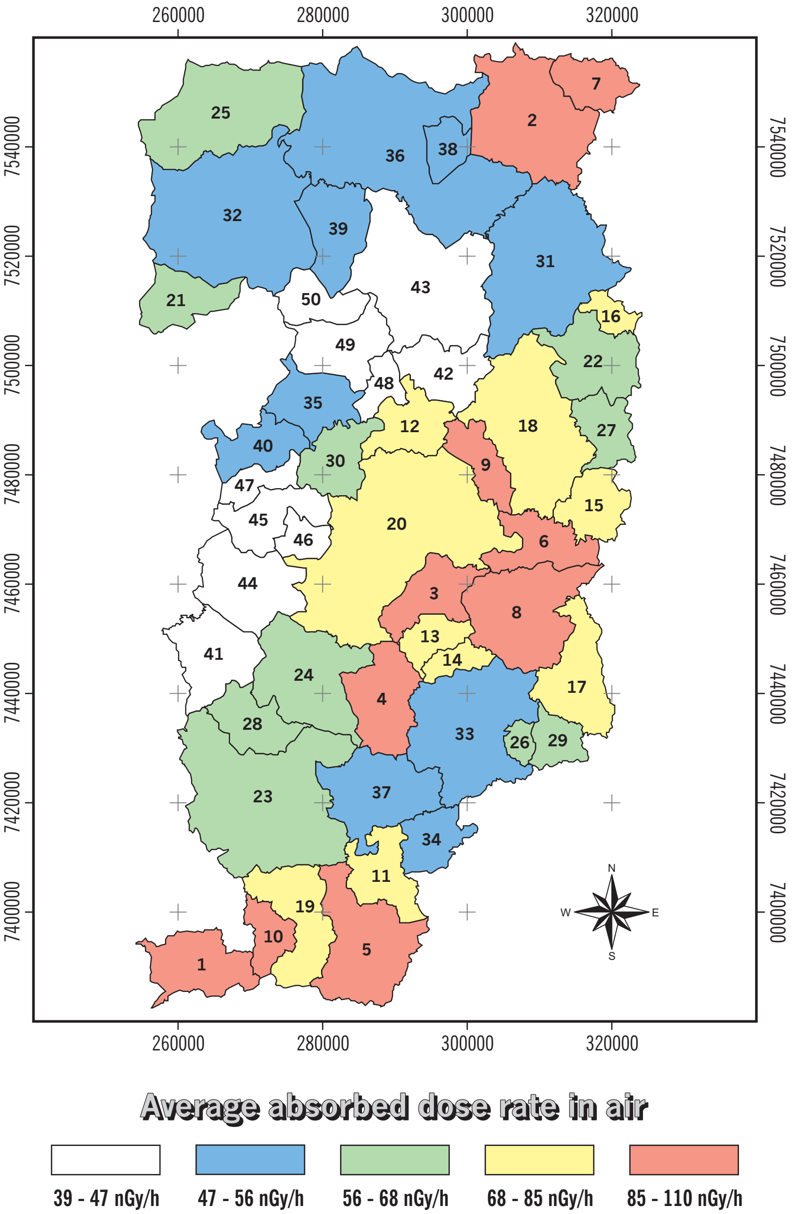

Figure 3 – Map of average radiation dose per municipality (average of profile points values that are within the municipal limits) of São Paulo State. The municipalities are numbered in descending order of average dose value (see table 1)

Since the effect of vegetation and soil moisture was not considered in the analysis, the estimates presented may be smaller than their real values. A difference of 27% was indicated by comparison between dose estimates obtained through terrestrial and aerial gamma spectrometric data for Itu Intrusive Suite.

The estimated radiation doses presented in this study are similar to published data for areas comprising analogous rocks and likewise, these gamma-ray dose levels show no indication of health hazards for human being.

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