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Radioactivity studies in Porto urban area: gamma radiation of the Paranhos sector

DIANA CRISTINA REIS DUARTE
Outubro de 2013

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Instituto Superior de Engenharia do Porto

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Estudos de radioactividade na área urbana do Porto: radiação gama do sector de Paranhos

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Dissertação apresentada ao Instituto Superior de Engenharia do Porto para cumprimento dos requisitos necessários à obtenção do grau de ***Mestre em Engenharia Geotécnica e Geoambiente****, realizada sob a orientação do Professor Doutor Antonio Vega y de la Fuente, Professor Adjunto do Departamento de Engenharia Geotécnica do* ISEP e da Professora Doutora Maria de Lurdes Proença de Amorim Dinis, *Professora Auxiliar do Departamento de Minas da FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO*.

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O Director do MEGG|ISEP

To my parents…

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Keywords

Radiation; Urban Radiation; Gamma radiation; Exposure; Radiation Doses; Public Health.

Abstract

A set of radiation measurements were carried out in several public and private institutions. These were selected with basis on the people affluence and passage to these sites. These measurements were registration formed either indoor, outdoor or underground and were compiled in three Case Studies. Radiation doses measurements were also made, surface and underground locations, and compiled in other two Case Studies.

There were sampled, at the same time, humidity, temperature, atmospheric pressure and relevant construction materials at sampling locations. They were collected and registration formed to analyse if there is any relation or contribution for the measured value in each specific place.

Geostatistical models were used to elaborate maps of the results both for radiation values and for doses. Preliminary relations were established among the measured parameters.

Palavras Chave

Radiação; Radiação Urbana; Radiação Gama; Exposição; Doses de Radiação; Saúde Pública.

Resumo alargado

Com o presente trabalho proceder-se-á ao levantamento de radiação da freguesia de Paranhos. O primeiro passo foi efectuar a selecção dos locais para que se pudesse iniciar o processo de medições- "sample sites". Sendo que estes locais teriam de ter como característica a aglomeração GISnificativa de pessoas dos grupos, entre outros, considerados de risco (idosos e crianças).

Desta forma, seleccionaram-se várias instituições que desempenham um papel importante para a freguesia de Paranhos, tais como: Bombeiros Sapadores, Clinicas, Hospitais veterinários, Hospitais, Jardins-de-Infância, Escolas (básicas, 2º ciclo, 3º ciclo e ensino secundário), igrejas, estações de metro (subterrâneas apenas), túneis do Porto, parques de estacionamento subterrâneos.

Seleccionaram-se dois equipamentos o Cintilómetro de radiação gama SPP2 NF (Saphymo) e GS-3 (GAMMA SCOUT®), sendo que o primeiro mede a radiação total (choques por segundo) e o segundo mede a dose de radiação (µSv/h).

Foram então adotados dois processos distintos de medições.

As medições realizadas com o SPP2 foram divididas em três categorias: Indoor (medições efetuadas dentro dos edifícios), Outdoor (medições efetuadas fora dos edifícios) e Underground (medições subterrâneas).

Em cada local foram efetuadas 5 medições junto ao solo e 5 medições a um metro do solo, sendo que o resultado final de cada medição será a média de cada uma. Para cada medição foram obtidos dois valores médios referindo-se a alturas distintas de medição, relativamente ao solo.

Para as medições com o GS-3 apenas foram consideradas duas situações: Surface (todos os locais medidos à superfície) e Underground (todos os locais subterrâneos).

Em cada local foram efetuadas duas medições (doses de radiação gama e doses de radiação total; ou seja alfa, beta e gama). Cada medição teve a duração de 10 minutos.

Ao mesmo tempo foram consideradas algumas variáveis como humidade, temperatura, pressão atmosférica, velocidade e direção do vento.

Antes de se proceder à análise geoestatistica da informação recolhida, foram elaboradas estatísticas gerais dos casos estudados (média, mediana, desvio padrão, mínimo, máximo, número de medições).

Mediante a utilização de modelos geoestatisticos (com recurso ao programa informático Surfer 8) foi gerada informação que foi utilizada posteriormente numa ferramenta de Sistema de Informação Geográfica (ArcGis), que permitiu gerar uma série de mapas que demonstram a distribuição geográfica da radiação gama. Este procedimento repetiu-se na análise das doses. No caso da radiação gama foram ainda analisados os desvios padrão das medições efetuadas a 1m do solo, de forma a perceber se os locais com valores de radiação mais elevados coincidiam com os locais de maior incerteza.

Estabelecendo valores de relação entre os dois equipamentos e entre as duas grandezas medidas, verificamos se os valores recolhidos refletiam algum tipo de padrão. Foi ainda elaborada uma primeira aproximação no que toca à relação da emissão de radiação gama e doses, com os tipos de materiais que constituem as infraestruturas sujeitas a medições. Finalmente foi estabelecida uma comparação entre os casos estudados (radiação e doses), verificando se existia alguma ligação entre os diferentes mapas gerados e relacionando os locais com valores mais elevados de radiação com causas como os materiais de construção. Existe ainda uma secção onde estão definidos quais seriam os trabalhos futuros mais adequados para posterior complementação dos estudos desencadeados ao longo desta tese.

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Introduction

1 Introduction

1.1 Objectives

Attending that this is a Geotechnical and Geoenvironmental Engineering master thesis it has several objectives that are writen down in order to guide the study. The problems that the exposure to radiation can generate for humans health in a short and long time was one of the reasons that make us adopt this study area in Porto: Paranhos sector. Therefore, the present work would have importance not only for the scientific community but also as a tool in the future of Paranhos sector development. The objectives established were:

- Radiation measurements in Paranhos sector;
- Measurements of radiation doses;
- Geoestatistical analysis of the collected, registration formed and adjusted to the theoretical models that better fit the distribution of the values;
- Compile general data as humidity, temperature, atmospheric pressure and construction materials;
- Development of radiation maps and radiation doses over the topographical map of Paranhos sector to make easier the perception of the variation from the radiation content in Paranhos. This was possible using GIS programs.
- Establish some preliminary correlations between general data, radiation and doses.

1.2 Brief history of radiation

"No light could come from the tube because the shield which covered it was impervious to any light known, even that of the electric arc... I did not think. I investigated."
Wilhelm Conrad Roentgen, 1896 (Weissmann, 2010).

Wilhelm Conrad Roentgen was born on March 27, 1845. His parents did not know that 50 years later, this little child would make one of the great discovers in science. It has all started on November 1895, at the University of Wurzburg, when Wilhelm Conrad Roentgen discovered X-rays. After that, he started several studies regarding his discovery. However, there are no details of all his experiments because he ordered to burn all his notes on his death. His discovery was a remarkable scientific achievement and it had important impacts on medicine and physics, allowing these two areas to grow exponentially (Patton, 1996; Frankel, 1996; Care, 2012).

The announcement of the discovery of Wilhelm Roentgen kept the attention of a very important French family of scientists, the Becquerel; Antoine Henri Becquerel was a physics scientist. As the rest of his family, he was trying to unroll some experiments in order to make some progress based on Roentgen discovery (Allisy, 1996). The French physics scientist based his studies on the discovery of X-rays and they discovered that uranium releases a similar radiation. Becquerel was trying to demonstrate a connection between minerals that glow when exposed to strong light and a new type of electromagnetic radiation, X-rays (Gramling, 2011). He and his student Marie Curie named this phenomenon as radioactivity. In 1903, these discoveries earned the Nobel Prize in physics for Antoine Henri Becquerel, Marie Curie and Pierre Currie, her husband (Frame, 2001). On the early twentieth century Antoine Henri Becquerel's research on radiation and radioactivity allowed many scientific advances such as radiotherapy.

After the discovery of radioactivity, the Polish couple of physicists, Marie and Pierre Curie, remained studying and they discovered two radioactive elements, Polonium and Radium.

Marie proposed the theory of radioactivity: elements transform themselves naturally through the years in order to lose energy that it is emitted as radiation.

The Royal Institution of London invited them to give a lecture about their discovery. Pierre Curie showed "how radium rapidly affected dosimetric photographic plates wrapped in paper, how the substance gave off heat and in the semi-darkness he demonstrated the spectacular light effect" (Froman, 1996). He also described the medical tests he had made on himself and mentioned the possibility to use radium in cancer treatments (Froman, 1996). After the death of Pierre Curie his wife keeps leading the studies on the treatment of cancer using radioactive elements. She died on 4 July 1934. An accepted cause of Marie's death was the years of radiation exposure she received (Frame, 2001; Yogananda, 2001; Care, 2012).

Despite of the works of all scientists described before, Ernest Rutherford is considered the father of nuclear physics. Rutherford created the language to describe the theoretical concepts of the atom and the phenomenon of radioactivity. He divided radiation and named the different types:

- Alpha rays;
- Beta rays;
- Gamma rays.

Therefore, he classified the various forms of existent radiation, which were almost unknown at his time. He described alpha and beta rays as particle beams and gamma rays as a form of high-energy electromagnetic radiation.

Rutherford achievements' were far from ending:

- On 1903, he was able to change direction of alpha rays with both fields: electric and magnetic.
- "Half-life" term surged when he observed the intensity of radioactivity falling with time.
- On 1906, an experiment of two of Ernest Rutherford's students, that "showed large deflections for a small fraction of indent particles" (Weisstein, 1996-2007), led him to propose that atoms were "nuclear" (Weisstein, 1996-2007).
- Rutherford showed, at the McGill University, that uranium and thorium transmuted by a radioactive process called decay.

Due to his work, Ernest Rutherford won 1908 Nobel Prize in chemistry (Campbell, 1999).

The radioactive scientific discoveries have continued through the years. The atomic bombs marked one of the worst moments in humankind's history. Alongside it was the turning point in radioactive history and to society as it has touched people's conscience. After the World War II the radioactive experiments in humans and animals were forbidden (Malloy, 2012).

1.3 Radiation/radioactivity, what is it?

Radiation is one of the most important fields of physics. Generally speaking, radiation is the transfer or emission of radiant energy, mostly as particles or electromagnetic waves. When emitted with high-levels of energy, radiation can be very dangerous, because it can damage human cells.

Atoms' nuclei can be unstable and suffer some changes through time, trying always to form lighter stable nuclei. Thus, nucleus will spontaneously decompose forming nucleus with higher stability. This process is known as radioactivity. The energy and particles released during this decomposition process is called radiation. Consequently, radioactivity is the spontaneous emission of particles or high-energy waves as consequence of atom nucleus instability. This energy and particles released are collectively named rays (Shuler, 2006).

The first radioactive elements discovered were Radium (Ra), Polonium (Po), Uranium (U) and Thorium (Th). Humankind lives with radioactivity since its existence because it is a natural process. Radioactive particles emitted through the decay process are extremely energetic. Decay is a process that consists in the nucleus disintegration; by this way it loses energy until it finds stability (Oxford, 2005). When radioactive particles penetrate cells, they can kill them or damage DNA originating illnesses as tumours (Gallavotti, 1997).

Atomic nucleus rupture is called nuclear fission. In this process, high quantities of energy are released. When a neutron reaches the nucleus of a fissile element it splits in two, releasing more neutrons that can interact with other nucleus; if the quantity of material is enough, it occurs a chain reaction. The nuclear fission process emits 100 million times more energy than a normal chemistry reaction (Fraioli, 2002; Chang, 2005; Cutnell, et al., 2010).

1.3.1 Radiation units (introduction)

To make radiation studies acceptable it is necessary to quantify it, by doing fieldwork.

The selected unit depends on what we want to measure. These units are mainly related to the type of equipment we employ and what it measures. Having always in mind what is the primary objective of the study.

Radioactivity, radiation absorbed dose, dose equivalent and exposure are the three main facts that we may measure when doing a radioactive study. In some kinds of radiation as X-rays or Gamma radiation is possible to measure the external and internal radiation dose to a whole body or just an organ (HPS, 2011). Radiation can be expressed by the following units (Table 1):

Table 1. Radiation measurement units

Unit	Symbol	Description/Application
Curie	**Ci**	**A Curie is a common unit of radioactivity.** It is also a large amount of radioactivity. A Ci is considered a measure of the rate (not energy) of radiation emission from a source.
Becquerel	**Bq**	**Becquerel's unit is used to report soil and food contamination, SI* unit of activity.** One Becquerel is an extremely small amount of radioactivity (One Bq is 1 disintegration per second, dps). As a Curie, this unit is also a measure of the rate (not energy) of radiation emission from a source. It is used when measuring radioactivity.
Rad	**Rad**	**Common unit of exposure it used to measure the absorbed dose. It is only applied to gamma radiation and X-rays.**
Gray	**Gy**	**We use it when measuring the absorbed dose. SI* unit (equal 100 rads).**
Rem	**rem**	**Common unit of human dose equivalent.**
Sievert	**Sv**	**Si* unit of human dose equivalent(equals 100 rem)**
Roentgen	**R**	**Common unit of exposure; applies only to gamma radiation and X-rays.**
Coulomb/Kilogram	C/Kg	**SI* unit used to measure exposure.**
Counts per minute	**CPM**	**Common units in the Geiger counter (equipment commonly used to measure radioactivity).**
Counts per second	**CPS**	
Dose equivalent	**H**	**Radiation protection.**
Quality Factor	**Q**	**Radiation protection.**

*SI-International system unit (CCOHS, 2007; U.S.NRC, 2012; EPA, 2013).

As it will be seen soon in this study different doses of radiation prorogue different effects on people. On Table 2 are quantified different doses of radiation in Sv and mSv (measures dose equivalent) and the respective health effects that may be felt by those who are exposed.

Table 2. Doses of radiation quantified and respective health effects

Dose of radiation	Health effects
10 Sv	Risk of death within days or weeks (acute health effect)
1 Sv	Risk of cancer later in life (5 in 100)*
100 mSv	Risk of cancer later in life (5 in 100)*
50 mSv	TLV for annual dose for radiation workers in any one year
20 mSv	TLV for annual average dose, averaged over five years

*In a population of 100 people, 5 have cancer (CDC, 2003; CCOHS, 2007).

The world average of absorption radiation doses is 2,4 mSv/year, 3 to 5 times lesser than when humans start to walk on earth. Despite this limit, the range varies between 1 and 10 mSv/year (UNSCEAR, 2000).

1.4 Sources of radiation

As already mentioned, radiation is energy that comes from a source and travels through outer space or atmosphere depending on its source (HPS, 2012). Radiation is, and always has been, all around us; therefore, all living creatures are exposed. Natural background radiation has been around us since the birth of the universe. Radiation has two main sources: natural and anthropogenic. There are many types of radiation according to its energy and wavelengths.

We can say that earth is a source of terrestrial radiation. The atmosphere surrounding the Earth and its magnetic field are natural shields to cosmic radiation; however, these shields make unable the exit of Earth's own radiation caused by its structure (WHO, 2013).

Over 60 radioactive elements (radionuclides) can be found in nature (Ravisankar, et al., 2011).

There are three different sources of natural radiation:

i) **Cosmic radiation:** cosmic radiation is present in the entire universe; therefore, high-energy particles originated in outer space bomb the planet Earth and its atmosphere every day. Cosmic Rays intensity decrease as they progress in Earth's atmosphere.

Cosmogenic radionuclides are radioactive nuclei originated by cosmic radiation. ^{3}H and ^{14}C are two of the most known cosmogenic radionuclides.

The majority of people live at low altitudes what allows them to experience similar annual doses from cosmic radiation. However, there are some cities at considerable altitude as Quito and La Paz in the Andes, Denver in the Rocky Mountains and Lhasa in the Himalayas, where the population may receive annual doses several times higher. The dose of cosmic radiation can be different depending on the type of building in which a person live or in an intercontinental flight at cruising altitude, the dose rate can reach a hundred times more than on the ground (UNSCEAR, 1993; Wrixon, et al., 2004; EPA, 2012; U.S.NRC, 2012).

ii) **Terrestrial radiation or Earth's radiation (include all radiation coming from earth structures as rocks, soils, and others):** As an example, we may quote radon, a naturally occurring radioactive gas. ^{222}Rn is a colourless, odourless, tasteless, radioactive, inert, gaseous element that is a natural component of the air we breathe. Radon gets into buildings mainly through cracks in floors or gaps around pipes or cables (Figure 1). Long-term exposure to high levels of radon can irradiate lung tissue and increase the risk of lung cancer (Clouvas, et al., 2011).

Almost 21 000 people die every year from radon induced lung cancer (EPA, 2012f). A recent study in a population-based case-control, using 2 400 cases of childhood cancer, showed a GISnificant association between residential radon exposure and acute lymphoblastic leukaemia risk, therefore children are considered a risk group in terms of radon exposure (Brauner, et al. 2010; F.Pacheco-Torgal, 2012; Martins, et al., 2013).

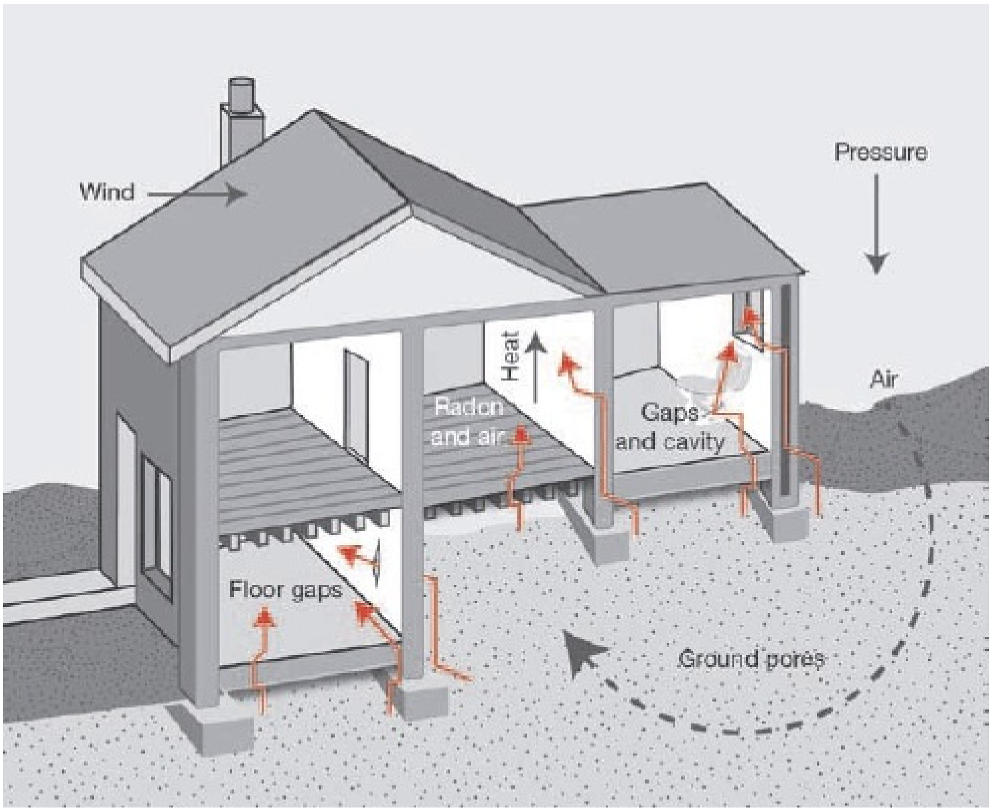


Figure 1. *"How radon enters a home"* (Wrixon, et al., 2004).

iii) **Internal radiation:** internal radiation is a naturally occurring type of radiation. It exists inside the human body due to the ingestion of food and water and due to the transfer from soil and air to the food chain food and water contain radionuclides such as ^{14}C, ^{40}K, ^{137}Cs, ^{3}H, ^{235}U, ^{238}U and ^{232}Th (Martins, 2010; Ravisankar, et al., 2011; U.S.NRC, 2012).

The World Health Organization has recently created a program to ensure that the benefits of radiation (including Earth's Radiation) are far from to exceed any risk. Nowadays Earth's natural radioactivity was increased by some accidents that affected the environment and the population all over the world. (WHO, 2013):

The other main source of radiation is anthropogenic. As an example of this kind of radiation we may point out:

iv) **Radiation used for health care:** This may be applied in two different ways: in diagnosis and therapy. "Both are intended to benefit patients and, as with any use of radiation, the benefit must outweigh the risk" (Wrixon, et al., 2004).

In some moment at people's lives, they take an X-ray examination to help physicians to diagnosis diseases or damages in the body. There are others diagnostic procedures much less common, which involves the administration of radionuclides to patients so that detectors outside the body can be used to observe how organs are functioning. Usually radiation doses used at these procedures are low; however, there are some procedures in which that same dose can be appreciable (Wrixon, et al., 2004).

With the advances in technology, the benefits of radiation in medicine gain recognition, therefore its use is still increasing (WHO, 2013). All the types of radiation produced by human's activities belong to anthropogenic sources. Radioisotopes as Iodine-131 (^{131}I), Caesium-137 (^{137}Cs), Americium (A), Tritium (^{3}H) and Polonium-210 (^{210}Po) are produced in some of humans' activities (nuclear weapons testing, nuclear waste disposal, transportation, storage, loss, and misuse of radioactive sources) (EPA, 2012; U.S.NRC, 2012).

1.5 Radiation types

Radiation has a wide range of energies forming electromagnetic spectrum. Radiations with high frequencies are more dangerous because of their penetration power in the human body. Radiation varies due to the wavelength and its frequency. The spectrum has two major divisions.

1.5.1 Non-ionizing radiation

Non-ionizing radiation causes atoms and molecules to vibrate, however, it has not enough energy to remove electrons from them and cause ionization (Júnior, 2012; EPA, 2012; WHO, 2013). Consequently, it has no energy to harm DNA. However, it may affect cells in other ways, but it cannot be established a relation between non-ionizing radiation and cancer. It could have natural or anthropogenic sources as cell phones, electrical devices, heaters and others.

Modern societies take advantage of the properties of non-ionizing radiation for quotidian tasks. Heating food, telecommunications, and broadcasting are some of the activities that take advantage of this type of radiation (Curtis, 2002; ACS, 2012; EPA, 2012):

This range of radiation can be divided into:

- Visible light radiation: $4.0x10^{14}$ - 7.5×10^{14} Hz (Russel, 2005);
- Infrared radiation (IR): $3x10^{12}$ - $3x10^{14}$ Hz (Michaud, 1999; Kurtus, 2010; Pierrehumbert, 2011);
- Microwave radiation (MW): $3x10^{9}$ - $3x10^{12}$ Hz;
- Radiofrequency radiation (RF): $<3x10^{8}$ Hz; (Hunt, et al., 2010; Vermont, 2012).
- Extremely low frequency radiation (ELF): 1 Hz - 300 Hz (OSHA, 2006).

Ultraviolet radiation (UV): 7.50×10^{14} – 3.00×10^{17} Hz establishes the barrier between Non-ionizing and Ionizing radiation. This statement is controversial; different sources classify UV radiation as:

- Type of radiation that only establishes a barrier and do not belong to non-ionizing radiation or ionizing radiation (Zeman, 2003; Russel, 2010);
- Non-ionizing radiation (Dreibelbis, 2004; OSHA, 2005; WHO, 2013);
- Ionizing radiation (EPA, 2010).

1.5.2 Barrier radiation: ultraviolet radiation

Attending to the three possible types of classification to UV radiation in this study; it was classified as a barrier radiation once it makes the transition of non-ionizing radiation to ionizing radiation.

Ultraviolet radiation is, as other radiation types, a range of the electromagnetic spectrum. Sun emits ultraviolet radiation; humans can feel it (Allen, 2001).

This kind of radiation has shorter wavelength and higher energy than visible light radiation, which means that is potentially dangerous. Ultraviolet radiation present three wavelength ranges:

- UVA, ultraviolet radiation A: this range tends to make skin cells old and damage its DNA. UVA is linked to long-term skin damage such as wrinkles but it is also the cause of some skin cancers, however, it is very important to our daily lives, as it stimulates vitamins production;
- UVB, ultraviolet radiation B: it is a range that is directly connected with damaged DNA and the cause of sunburns. UVB can be pointed as the cause of most skin cancers. This kind of radiation is also very important to our daily lives, as it also stimulates vitamins production;
- UVC, ultraviolet radiation C: this range is not able to pass through our atmosphere and therefore it is not present in sunlight. Normally UVC is not classified as a cause of skin cancer.

Vitamin D is generated by short exposure to UVB; depending on an individual’s skin type can also be lead to sunburns. According to US Environmental Protection Agency (EPA), atmosphere’s stratospheric ozone layer shields us from most of UV radiation. However, what does get through the ozone layer can cause problems on human health, such as skin cancer, cataracts, and suppression of the immune system and premature aging of the skin.

Unfortunately, benefits of sunlight cannot be separated from its damaging effects; it is important to have always present the risks of overexposure to UV radiation; since it may cause chronic health effects (EPA, 2010; ACS, 2012; WHO, 2013).

1.5.3 Ionizing radiation

In nature, all the matters have the tendency to reach an equilibrium suffering different degrees of transformation until they find their stability. Ionizing radiation has sufficient energy to remove electrons, creating ions. In this process, radioactive elements (elements with unstable nucleus) emit energy or particles as protons, electrons or neutrons. This type of radiation is natural, but some artificial processes can also induce the production of ionizing radiation. It has high frequency, and it could cause bad health effects in living beings. Some elements in nature, such as rocks, soils and some construction materials, have the potential to emit ionizing radiation. The decay of some natural elements present in Earth’s Crust, as Potassium (^{40}K), Uranium (^{235}U, ^{238}U)

and Thorium (^{232}Th), generate ionizing radiation. These are some of the relevant isotopes that originate extensive decay chains. Figure 2 is an example of the decay chain of ^{238}U (HPS, 2011).

There are diverse kinds of ionizing radiation (Hall, 2013; WHO, 2013):

- ❖ Alpha particles (α);
- ❖ Beta particles;
- ❖ Gamma radiation or gamma rays (ϒ): 10^{20} - 10^{25} Hz;
- ❖ X-rays: $3x10^{17}$ – 10^{20} Hz.

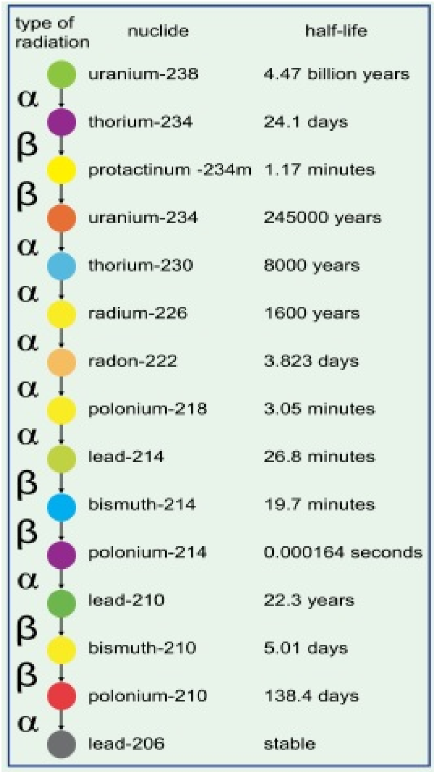


Figure 2. Uranium 238 decay chain. (Hall, 2013).

1.5.3.1 Alpha radiation (α)

Alpha particles or alpha radiations are two valid ways to name this type of ionizing radiation. It consists on the emission of alpha particles (α) by the nuclei of unstable atoms. Alpha particles (are considered large subatomic fragments; two protons and two neutrons; identical to the nucleus of a helium atom) (EPA, 2012g).

Due to its large mass and charge, alpha particles produce ions when they collide with atoms, in a very specific area and lose some of their energy each time it produces an ion (the positive charge pulls electrons away from atoms in its path). Finally acquiring two electrons from an atom at the end of their path to become a complete helium atom. An alpha particle has a short range in the air and cannot penetrate the outer layer of skin (EVS, 2005).

These particles are heavy and charged, and they tend to react strongly with matter; however, they are not very penetrating. If an alpha-emitting nuclide is deposited in an organism, alpha radiation can be extremely damaging.

In Table 3 are presented some radionuclides that emit alpha particles.

Table 3. Radionuclides that emit alpha particles.

Alpha emitters:	Symbol:	Atomic number:	Most common isotopes:
Americium, (EPA, 2012a)	Am	95	241Am
Plutonium, (EPA, 2012b)	Pu	94	236Pu; 238Pu; 239Pu; 240Pu
Uranium, (EPA, 2012c)	U	92	238U; 235U; 234U
Thorium, (EPA, 2012d)	Th	90	232Th
Radium, (EPA, 2012e)	Ra	88	226Ra; 224Ra; 228Ra
Radon, (EPA, 2012f)	Rn	86	220Rn; 222Rn
Polonium, (EPA, 2012g)	Po	84	210Po

Alpha particles interact with other matter through two main mechanisms:

- **Ionization**

This process occurs whenever an alpha particle is close to an electron pulling it out from its orbit (this phenomenon is called Coulomb Attraction). Each time this happens, that same alpha particle emits energy and it is slowed. It occurs when an alpha particle is able to strip away an atom's orbital electron, creating a positive charged ion. In the meantime, the electron joins the alpha particle, lowering the electric charge to -1; this phenomenon is called ion-pair formation. This process might continue building secondary ion-pairs until a chain reaction occurs; it is initiated by the primary and secondary ionizations that were originated by the alpha particle (Smith, 2010).

- **Excitation**

This mechanism occurs less frequently than ionization. It happens when an alpha particle's collision with an electron and it rises to a higher level. These alpha particles lose energy by exciting orbital electrons however, these interactions are not sufficient to cause ionization. Then, when the electron falls back to its original shell, the excess of energy is emitted. Only a small portion, less than 5% of the alpha particle energy, is released and because of its insufficiency in overcoming electronic binding energy; electrons are not removed from the target atom (TESEC, 2008; Smith, 2010).

1.5.3.2 Beta particles (β)

Henri Becquerel discovered this kind of radiation, which is also known as beta particles.

Beta particles are smaller and more penetrating than alpha particles but their power to go through tissue is still limited. It only penetrates human tissue until *the "germinal layer"* (area where are produced new cells) (HPS, 2011). However, clothes can provide some protection against beta radiation.

A positron (considered an anti-electron or antimatter equivalent of an electron) collides with an electron and the two particles annihilate each other, producing two gamma rays *("usually 100% of the mass of both particles is converted into energy")* (Gamble, 2010).

At the formation of a positron, small particles are also formed; these are considered nonzero mass, called neutrinos (Grande, 2008).

The amount of beta energy converted into photons is directly proportional to the energy of the beta particle. In some cases, a very dense material such as lead can be ineffective in stopping beta particles because they can produce secondary radiation when passing through elements with high atomic number and density (EVS, 2005).

There are many beta emitters; in Table 4 are presented the most important isotopes (Gamble, 2010; HPS, 2011; EPA, 2012):

Table 4. Beta radiation emitters.

Name	Symbol	Isotopes
Tritium	H	^{3}H
Cobalt	Co	^{60}Co
Strontium	Sr	^{90}Sr
Technetium	Tc	^{99}Tc
Iodine	I	^{129}I;^{131}I
Caesium	Cs	^{137}Cs

1.5.3.3 Gamma rays (ϒ)

In 1900, the physicist Paul Villard discovered the gamma rays “*Gamma rays are produced in the disintegration of radioactive atomic nuclei and in the decay of certain subatomic particles.”* (Stark, 2013). As all kinds of radiation, gamma radiation is the correction of energy in the radionuclide from a higher energy state to a more stable state (Smith, 2010).

Gamma photons have about ten thousand times as much energy as the photons in the visible range of the electromagnetic spectrum. Gamma photons have no mass and no electrical charge; they are pure electromagnetic energy. Due to their high energy, gamma photons travel at the speed of light and can cover hundreds to thousands of meters in air before spending their energy. They can pass through many kinds of materials, including human tissue. In order to stop or slow gamma photons commonly is used lead for shielding rooms. The wavelengths of gamma photons are so short and to measure them it must be used a nanometre (EPA, 2012).

This type of radiation may be very dangerous: they are not easily blocked and they are able to penetrate most materials including the human body (Figure 3). Gamma rays can be extremely dangerous to the living cells; in some cases, they can damage the biological cells causing severe illness or even death.

When gamma radiation collides with atoms, it ejects electrons from it (it happens when this type of radiation pass through matter).

Although all the bad aspects of gamma radiation, we need it in our daily lives, even to treat health problems as cancer. At Table 5 are shown the radioisotopes that produce gamma radiation and their applications (Science.Channel, 2011).

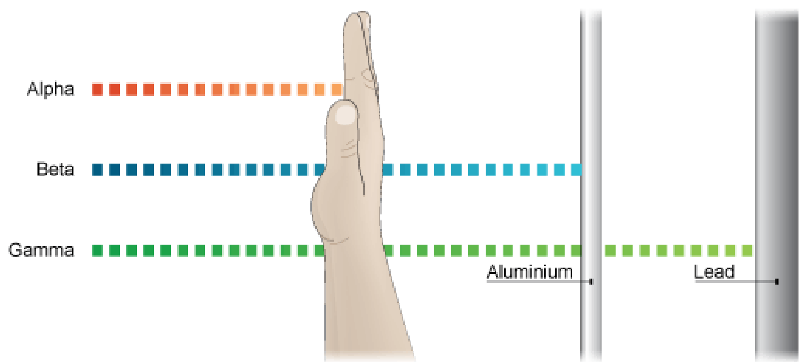


Figure 3. Types of radiation and shielding.

(http://www.bbc.co.uk/schools/gcsebitesize/science/edexcel/electromagnetic_spectrum/electromagneticspectrumrev5.shtml).

Table 5. Gamma emitters and their applications.

Element	Radioisotope	Used for:
Caesium, (EPA, 2012h)	^{137}Cs	*"Cancer treatment.* *Measure and control the flow of liquids in numerous industrial processes.* *Investigate subterranean strata in oil wells.* *Measure soil density at construction sites.* *Ensure the proper fill level for packages of food, drugs and other products."*
Cobalt, (EPA, 2012i)	^{60}Co	*"Treat Cancer.* *Sterilize medical equipment in hospitals.* *Pasteurize certain foods and spices.* *Gauge the thickness of metal in steel mills."*
Technetium, (EPA, 2012j)	^{99}Tc	*"Diagnostic studies (Different chemical forms are used for brain, bone, liver, spleen and kidney imaging and also for blood flow studies)."*

As mentioned before, this is a very high-energy and highly penetrating ionizing radiation. Sealed radioactive sources and machines that emit gamma radiation constitute mainly an external way of exposure to humans (HPS, 2011).

1.5.3.4 X-rays

X-rays can be defined as a form of invisible and high-frequency electromagnetic radiation. One of its characteristics is to carry energy and deposit a part of this energy within the body as it passes through. They are capable of penetrating the human body, which permits the generation of pictures showing internal structures of a human being (Radiologyinfo, 2012).

This kind of radiation is very used in medical treatments. The energy absorbed in this process has the potential to produce some biological effects within the tissue. The amount of energy absorbed in the tissue is known as radiation dose. Very large radiation doses are used in radiation oncology or therapy to stop the multiplication of cancer cells (Smith, 2010; IAEA).

Other very important characteristic of X-rays is the production of an image record, usually on a computer with the internal structure of a body (Figure 4). This is possible as the X-ray machine sends individual X-Ray particles through human body, generating those images. Bones appear white because they block almost all the X-ray particles (dense structures). Muscle, fat and fluid appear black or as shades of grey (structures that contained air) (Vorvick, 2013).

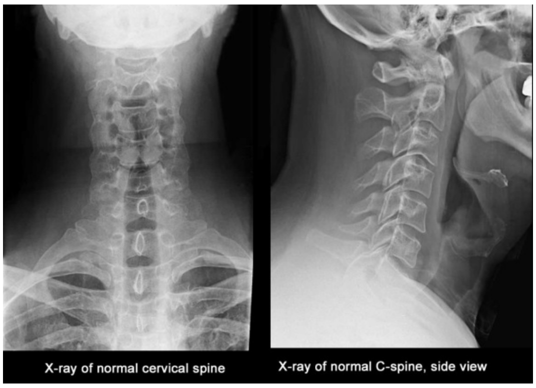


Figure 4. Spinal diagnosis X-ray (http://www.cedars-sinai.edu/Patients/Programs-and-Services/Spine-Center/Conditions-and-Treatments/Diagnostic-Studies/Spinal-Diagnostics-X-Rays.aspx).

1.6 The effects of radiation on human health

People started to think about radiation and its biological effects on living cells and how biological effects can diminish the quality of human beings life. As explained before, when a type of radiation with high-energy passes through material, it causes ionization. If this material is biological, as cells in human tissues and organs, the DNA of these cells can be damaged. Thus, the organs or tissues that the affected cell makes part can suffer some changes, putting in risk the normal functioning of the organism. However, cells have natural mechanisms that allow them to correct these damages; if the organism cannot repair the damage by itself, it sacrifices the cell by natural processes (UNSCEAR, 2013).

The type and intensity of the radiation exposure can affect the cells in three different ways (U.S.NRC, 2012):

- Injured or damaged cells repair themselves (there is no residual damage);
- Cells died (it happens every day with millions of cells, for several reasons, including overexposure to radiation);
- Cells repair themselves incorrectly; resulting in biophysical change (this kind of effect can even cause death in the affected organisms).

The severity or type of the health effect depends on the amount (dose) and duration of the radiation exposure. Health effects produced by radiation can be gathered in two broad categories (Muckerheide, 2000; EPA, 2012):

- ❖ Stochastic effects: this kind of health effect is connected with long-term and low level exposure to radiation. Thus, increased levels of radiation exposure make these kinds of effects more likely to occur; however, they do not influence the type or severity of the effect;
- ❖ Non-stochastic effects: non-stochastic effects are directly related with exposure to high levels of radiation; when the exposure increases, it becomes more severe.

1.6.1 Stochastic effects

Stochastic effects also known as late effects and are caused by long-term exposure to low levels of radiation. Cancer, an uncontrolled growth of cells, is considered a very common late effect. Usually, natural processes control the rate at which cells grow and replace themselves. They also control the body's processes for repairing or replacing damaged tissue. When some type of damage at the cellular or molecular level occurs, this process can be disrupted and it allows the uncontrolled growth of cells. There is also the possibility of other diseases occur; however, all are related with induced DNA mutation on living cells. Many years must pass before a given cell and its progeny gain sufficient importance to result in a clinical condition. Leukaemia is a type of cancer that do not needs many years of exposure to appear. The diminishing of fertility is also named a stochastic effect (UNSCEAR, 2001).

1.6.2 Non-stochastic effects

Non-stochastic effects or early effects are produced by exposure to high levels of radiation inducing mostly non-cancerous diseases. In cases of very high levels of radiation exposure, they can even cause death. These kinds of effects came from "acute" exposure to radiation and tend to show themselves quickly. Early effects result on various acute radiation symptoms. Non-stochastic effects can also be noticed when cancerous patients are being treated, once in the treatments they receive relatively high doses of radiation (EPA, 2012). According to Radiation Effects Research Foundation (RERF) most of the information about these symptoms was obtained based on interviews to more than 100 000 atomic-bomb survivors from 1956 to 1961 (RERF, 2003). Hair loss is one of the acute radiation symptoms recalled by survivors. We can see this effect in patients with cancer when doing the respective treatment. Is also regarded as the most reliably reported; it is considered to be remembered more objectively than other symptoms. Hair is made of protein, which is formed by a cluster of cells residents on the hair follicle. When exposed to radiation or toxic chemicals, such as chemotherapeutic agents for cancer, these cells die. Fever, nausea, vomiting, less of appetite, bloody diarrhoea, sores in throat or mouth also known as nasopharyngeal ulcers, necrotic gingivitis and purpura, also known as bleeding under the skin, were the most common symptoms experienced by heavily exposed survivors in the days or weeks following the atomic bombings in Hiroshima and Nagasaki, Japan (RERF, 2007; RERF, 2007).

1.7 Radioactive accidents and their effect on survivors health

Until the first radioactive episode occurs (Hiroshima atomic bombing), the real effects of radiation in health were unknown, therefore the study of these occurrences allowed to relate radiation with its biological consequences.

Five radioactive episodes from history are focused:

A. Hiroshima and Nagasaki (atomic bombings);

B. The Three Miles Island (nuclear accident);

C. Chernobyl (nuclear accident);

D. Semipalatinsk (nuclear weapons);

E. Fukushima (nuclear accident).

A. Hiroshima and Nagasaki

The first radioactive episode in the world happened on 6 August 1945, in Hiroshima, Japan. The president of United States of America, Mister Harry S. Truman, took the decision of releasing the atomic bomb (Kelly, 2013). Three days later, on 9 August 1945, that decision was repeated in Nagasaki. About 620.000 persons were exposed to a high dose of radiation. From this number about 210.000 persons died; the remaining ones were called the atomic-bomb survivors and their health problems were just about to start (HICARE, 2013).

According to Radiation Effects Research Foundation (RERF) there were three main effects among the atomic-bomb survivors:

- ❖ Acute Radiation Syndrome: collective illnesses that occur after exposure to high-dose (from approximately 1-2 Gy to 10 Gy) radiation within a few hours to months. This syndrome has the main symptoms and GISns of radiation poisoning, like vomiting within a few hours, followed within days to weeks by diarrhoea, reduced blood cell counts, bleeding, hair loss and temporary male sterility (RERF, 2003; RERF, 2007).

- Acute death due to radiation: Acute death is defined as death within two months of exposure. The dose received influence the probability of dying directly from radiation exposure. LD50, commonly known as 50% lethal dose, used as an index, express the dose at which 50% of population dies. At LD50 level, the main causes of death are bleeding and infection due to immunodeficiency resulting from bone marrow depletion. Recovery from such depletion sufficient to prevent death occurs within two months. Early estimates from survivor interviews measured the LD50 in terms of the distance from the hypocentre at which 50% of people survived: 1.000 to 1.200 meters in Hiroshima and 1.000 to 1.300 meters in Nagasaki.

However, the dose estimate was not possible at that time because there was no sufficient basic information. For example, radiation cataract (lens opacity) causes partial opacity or cloudiness in the crystalline lens and results from damaged cells covering the posterior surface of the lens. Symptoms can appear as early as one or two years following high-dose exposure and many years after exposure to lower doses (RERF, 2007).

The largest dose of radiation was received by those who lived in a zone of two km far away from the hypocentre of the atomic-bombing. Besides, all the people who entered the city of Hiroshima or Nagasaki soon after the occurrence and the ones in the black rain areas were exposed to radiation. In addition, some people were suffered the radiation from black rain containing nuclear fission products *("ashes of death"), and others to radiation induced by neutrons absorbed by the soil upon entering these cities soon after the atomic bomb detonation. "However, radiation doses from black rain or by early entry into the cities have not been calculated in detail"* (HICARE, 2013).

The location is represented below on Figure 5.

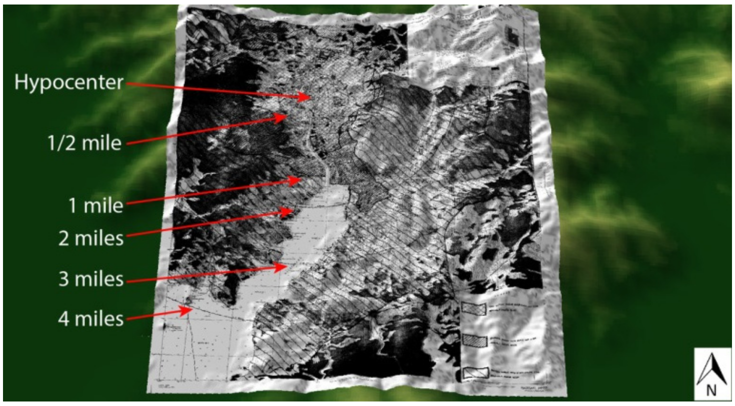


Figure 5. Hypocentre of the atomic-bombings in Nagasaki.
(http://nagasakiandhiroshimabombing.weebly.com/uploads/1/5/5/0/15501076/6527999_orig.jpg?698)

B. The Three Miles Island

The United States of America's worst radioactive accident occurred at The Three Mile Island nuclear power plant (Figure 6) on March 28, 1979, at Dauphin County, Pennsylvania.

This accident occurred due to a partial nuclear meltdown in one of the two nuclear reactors at this nuclear power plant. The partial meltdown resulted in the release of small amounts of radioactive gases and radioactive iodine into the environment. It happens to be the worst accident in U.S. commercial nuclear power plant history.

The Three Mile Island accident was considered a human error, as the workers turned off the cooling system from the reactor leading to its partial meltdown. (Gazit, 1999)

Figure 6. Power plant The Three Miles Island
(http://www.ontheissuesmagazine.com/2011spring/2011spring_Charman.php).

A combination of several facts permits the occurrence of the second radioactive episode in humankind history, being the first one in United States of America. Design deficiencies, personnel error and component failures allowed this accident to occur. It has changed forever the American nuclear industry and the United States Nuclear Regulatory Commission (NRC).

The newspapers start publishing articles saying that the health effects due to the incident would be devastator. The number of cancers and genetic mutation would increase exponentially, diminishes the quality of life of those who lived nearby the power plant, being death possible in cases of overexposure. Despite all the fear and news there were no health effects in consequence of this radioactive incident. This helped society to forget the accident.

Some research institutions as the United States Environmental Protection Agency (EPA) arrived immediately to the location of the accident with its experts in radiation. They take monitoring equipment and started to measure all around the power plant to assess the potential for radiation exposure of the ones who lived near the power plant. After the accident EPA remained in the area along eight years to monitor the radioactive air content (FlinchBaugh, 1980; Flichbaugh, 1981; Forman, et al., 2004; U.S.NRC, 2012; EPA, 2012).

C. Chernobyl

The second radioactive episode occurred on 26 April 1986, in Chernobyl, the northeast region of Ukraine. This accident occurred because one nuclear reactor had technical problems and released a radioactive cloud contaminating people, animals, environment and several kilometres of soil.

It is said that the Chernobyl accident released 300 times more lethal radioactive fallout than the Hiroshima bomb during ten days and scattered in different directions as the wind shifted. Fallout in the form of dust or rain was scattered on earth and people was exposed to radiation (HICARE, 2013).

The victims of this accident were divided into four groups:

1. Plant operators and fire fighters at the time of the accident;
2. Workers involved in the recovery and clean up after the accident;
3. People evacuated from the 30 km zone immediately after the accident;
4. Residents in the highly radioactive contaminated zone.

Within the first three days, 299 persons suffered from acute radiation sickness; they were sent to a specialized treatment centre in Moscow and some hospitals in Kiev. The priority was to examine victims and in the following days about 200 people were examined.

The effects felt by those who were at the power plant at the time of the accident depended essentiality on the way they were exposed (Figure 7) and the dose of radiation. The exposure occurred mainly by three different ways (Guskova, et al., 1998).

- By external, relatively uniform gamma-radiation;
- By deposition of beta/gamma-emitting nuclides on the skin.
- By ingestion of radionuclides.

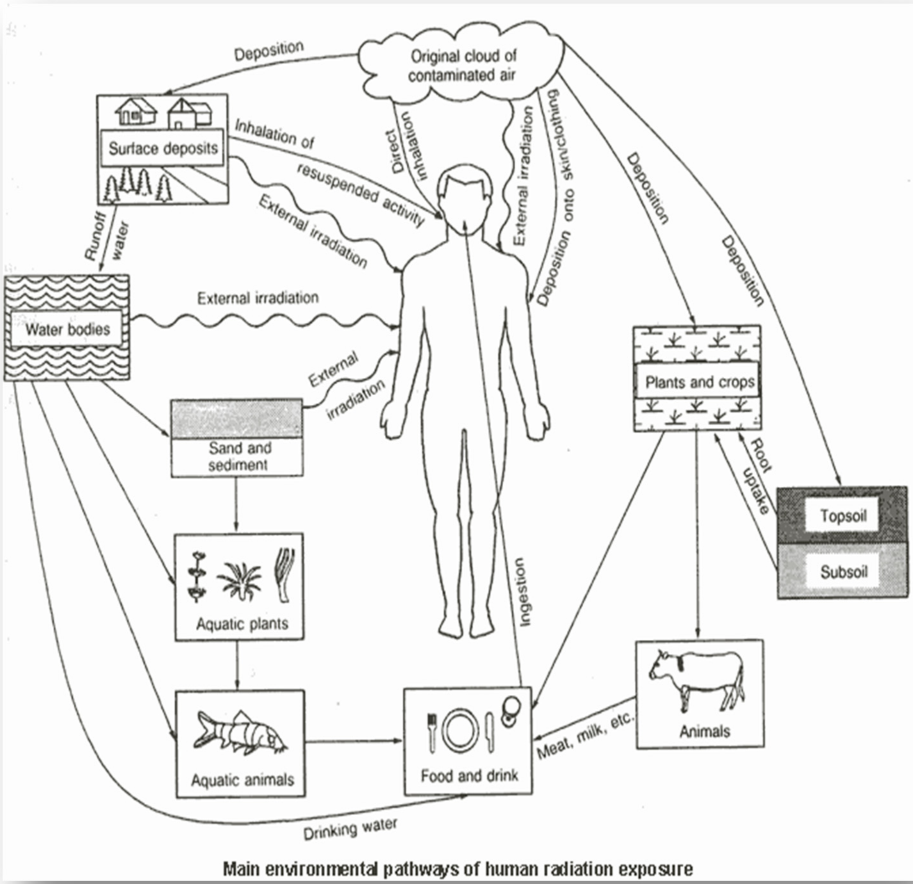


Figure 7. Main environmental pathways of human radiation exposure (http://www.world-nuclear.org/info/Safety-and-Security/Safety-of-Plants/Chernobyl-Accident/#.UWWF05PvuoA).

These episodes help to change the attitudes of people about nuclear safety on global scale. Radiation standards and strategies were reviewed to improve security. The studies carried out due to these radioactive occurrences help to gain knowledge about radiation health effects with low and high dose (UNSCEAR, 2001; World.Nuclear.Association, 2012; WHO, 2013).

In this radioactive accident, the number of people that was exposed varies between 1.6 and 9 million people (Figure 8). From these victims is known that 30 died in the first days due to acute radiation injury. It has affected the Soviet Union and all Europe, once the winds transport all of this radiation (HICARE).

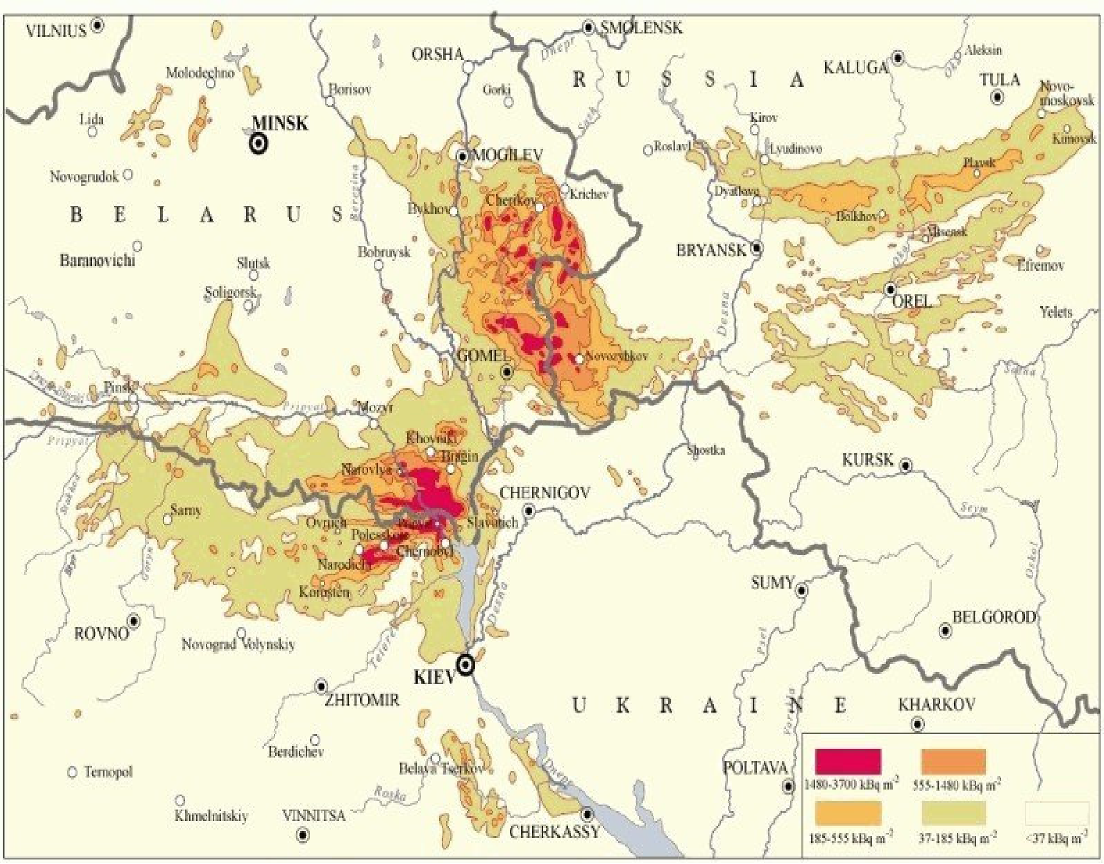


Figure 8. Map showing the affected areas by Chernobyl accident (http://decarbonisesa.files.wordpress.com/2013/02/contaminationmap_cs_beukru_fig_vi.jpg).

D. Semipalatinsk

After the World War II the Republic of Kazakhstan (Semipalatinsk at that time) located immediately at south of Russia, west of China, turn to the first centre for nuclear weapons testing within the Soviet Union. It was situated 800 km north of Almat (IAEA, 2012).

Semipalatinsk was a testing site built by the Soviet Union with one goal, testing nuclear weapons. This was also a city and never identified on official maps, as it was supposed to remain secret. The flow of people in and out of town was strictly controlled. Later, its name was changed to Kurchatov (the name of the man that helps Soviet Union obtaining the atomic bomb).

It has started to operate in 1949 and finished its activity on 1989. During many years, the Soviet Union made 456 (340 underground and 116 atmospheric) nuclear tests at Semipalatinsk test site. To measure shockwaves produced by explosions the Soviets built some buildings, some pretty similar to an aircraft wing (Figure 9).

Figure 9. Geese in form of an aircraft wing (http://io9.com/5988266/the-tragic-story-of-the-semipalatinsk-nuclear-test-site)

When performing the tests, they did not regard for the local population's health and safety; nowadays, passed 64 years from the beginning, the local population is still feeling its effects.

The first bomb exploded on 29 August 1949 and it was a plutonium bomb (Carlsen, et al., 2001).

Soviet authorities hid the data relative to the full impact of radiation exposure for many years; it has only became public when the testing site was closed in 1991 (Kessenova, 2009). When this facility was closed, local population had to live with the long terms health effects, the arid ground and polluted waters.

Nowadays the inhabitants of Kurchatov are free; however, they cannot eat anything that grows on those soils or drink water from the rivers or lakes (NTI, 2011).

E. Fukushima

More recently, on 11 March 2011, the great east Japan earthquake and following tsunami caused a nuclear accident at the Fukushima Daiichi Nuclear Power plant of Tokyo Electric Power Company (TEPCO).

On 10 March 2012, the number of confirmed deaths and missing people was about 19 000. From all the deaths, 95% was caused by the tsunami.
The earthquake occurred in the Pacific Ocean floor at a depth of around 24 km. Its epicentre was 130 km east of Sendai, 373 km northeast of Tokyo and 70 km northeast of Fukushima Daiichi nuclear power plant housing 6 reactors (USGS, 2011). This nuclear accident was possible once the emergency core cooling system did not worked on due to the complete loss of energy supply. In the units one, three and four occurred several hydrogen explosions (Figure 10), therefore a significant quantities of radioactive material were released into the atmosphere.

Figure 10. Fukushima hydrogen explosions (http://thinkprogress.org/wp-content/uploads/2013/01/japonia-fukushima.jpg)

Tokyo Electric Power Company (TEPCO) had a large number of workers doing all the necessary efforts for stabilizing the nuclear power plant. The exposure of these workers was the most important concern; some were exposed to more than 250 mSv of radiation during the initial response phase. After the accident, the primary goal was to evacuate all the residents within 20 km of the plant (Mori, et al., 2013; Fushiki, 2012).

On December 2011, TEPCO declared that the nuclear power plant had been brought to a safe state of cold shutdown. The temperature of the reactor pressure vessel in the affected units are below 100 ºC, and radioactive emissions from the power plant are now acceptable (do not exceed one mSv/year). So far, no radiation deaths have been announced.

Nuclear power was used to supply one third of the nation's electricity. All Japan's nuclear power plants were closed after this disaster, however, two were reopened to help struggling economy (Kazunori, et al., 2012; Srinivasan, et al., 2012; Figueroa, 2013).

1.8 Urban radiation

Naturally, radionuclides would behave differently attending to the environment type: rural or urban (HWANG, et al., 2008). The social behaviour of human beings that live in groups and build houses, streets and cities to provide shelter changed the ways humans are exposed to radiation (Asimakapoulos, et al., 2001).

Chernobyl accident was the reason why the impact of radioactive contamination in cities, towns and villages restarted being discussed. This was the evidence that nuclear accidents could lead to significant long-term contamination and radiation exposure problems after radioactive dust deposition in urban areas (where most people actually live) (Gluzman, et al., 1992; Andersson, 2006). The interest on radionuclides behaviour in urban environments has increased meaningfully, alongside with urban radiation studies.

As mentioned before, radiation can be trapped in buildings, attending to building materials: their radioactive content. Environment radiation can also be trapped in buildings (cracks in floors or gaps around pipes or cables) (Clouvas, et al., 2011). Therefore, keeping urban areas clear of radionuclides providing a healthy environment is a matter of concern nowadays (HWANG, et al., 2008; Thiessen, et al., 2008).

Radioactive materials, as other types, when released into the environment will be deposited on surfaces due to several natural facts as: atmospheric turbulence, precipitation or gravitation. There are two types of deposition, dry deposition, and wet deposition. According to Won Tae Hwang, Moon Hee Han, Hyo Joon Jeong and Eun Han Kim "*Dry deposited radionuclide is assumed to be either mobile or fixed to surfaces. If it is mobile radionuclides, it can be removed from surfaces by rain, but if it is fixed ones, it cannot be easily removed. If there is no precipitation during a contamination of air, dry deposition will consist of a mobile fraction and a fixed one.*" (HWANG, et al., 2008). According the Izimir Institute of Technology, wet deposition refers to acidic rain, fog, and snow. "*¾ in wet deposition, there are always some atmospheric hydrometeors* *which scavenge aerosol particles. This means that wet deposition is gravitational, Brownian and/or turbulent coagulation with water droplets"* (Aytaç, et al., 2012).

Occurrences which consequences would be the diffusion and deposition of radionuclides require studies to determinate the impact on population. It is important to estimate the number of people affected and the economic costs of recovery in extreme cases (Thiessen, et al., 2009).

To analyse the gravity of the event we must:

- Collect data such as radionuclides content in specific places. To elaborate several maps to see the spatial distribution and determine where the values exceed the ones figured as limit by the law. To take providences to diminish the values over the limits.
- Sometimes there is a registration form of the radioactive data collected before the event and in these cases, it is possible to establish a comparison. After the occurrence, new sampling and assessment campaigns are carried out to update and complete the data. New maps are elaborated and new comparisons are made.

The maps can be based on geostatistics analysis of the collected data, or other mathematical models. Independent of the chosen path at the end it is necessary to estimate which would be the consequences for the population, the economic costs associated to recovery of the sector and establish measures to diminish the consequences on humans' health.

Therefore, this kind of studies carried out on urbanized areas has as main objective the prediction of changes in radionuclide concentrations. When the values are above the limit allowed by the law it is necessary to carry out some remediation efforts. The Urban Remediation Working Group developed some activities that can help in diminishing radionuclides concentrations (IAEA, 2007).

Among the institutions that usually make these studies are IAEA with the Urban Remediation Working Group and the Faculty of Science of Cairo, Giza, Egypt.

The Faculty of Science of the Cairo University chose a different path to its studies. They investigated the effect of urbanization processes on the solar radiation components; through collected monthly mean values of global and ultraviolet solar radiation incident at Cairo urban area during two different periods (1969-1973) and (1993-1997) (Robaa, 2004).

These are two examples of possible studies carried out in urbanized areas, always focusing on the radiation theme and all the consequences it could bring to people life.

However, there are several kinds of paths to do urban radiation studies. At the urban areas of the northern highlands of Jordan was determinate natural radioactivity, by means of gamma-ray spectrometry system in surface soil samples collected from various geological formations (Ibrahim F. Al-Hamarneh, 2008).

In this particularly study radioactive data was collected (gamma radiation and total radiation). Several maps were elaborated based on the geostatistics analysis in order to understand the spatial variability of the radiation taken measurements.

Characterization of the studied sector

2 Characterization of the studied sector

Porto was the chosen area to develop the propose study. Porto is mainly a granitic area; therefore, the natural radionuclides concentration was expected to be higher. This means that the general population may be exposed to higher doses of radiation.

Within Porto, Paranhos was the sector to focus the present study for being the most populous one. Paranhos is also the fifth biggest borough of Portugal. All the sectors of Porto's area are represented in Figure 11 and Figure 12 and shows the number of inhabitants of each sector; emphasising that Paranhos is indeed the most populous borough.

Figure 11. Boroughs of Porto city.

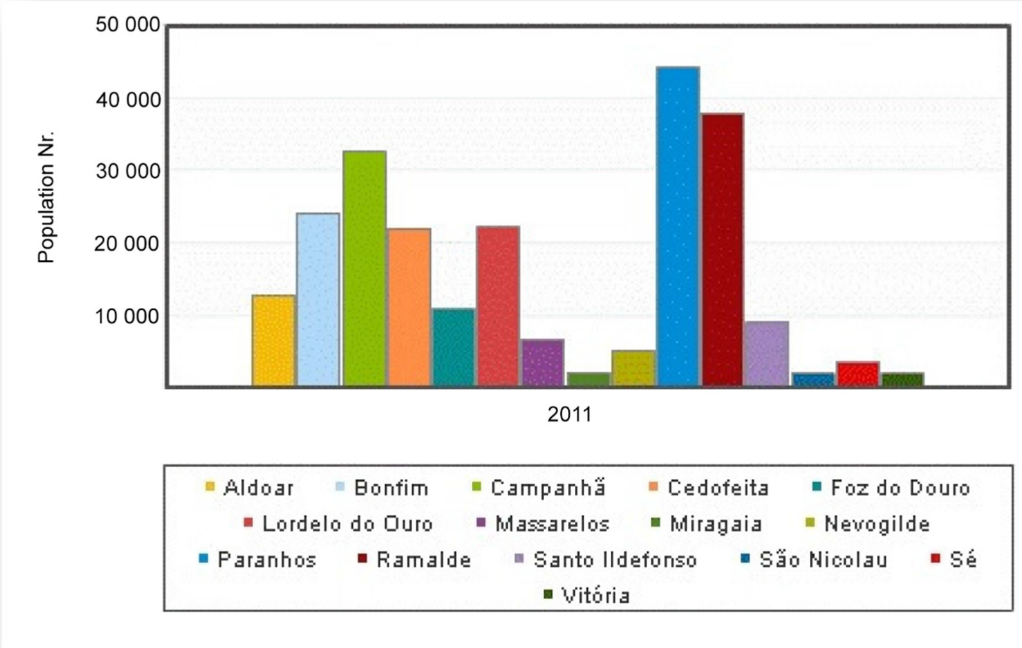


Figure 12. Porto's boroughs and the respective population. Adapted from: (http://www.jfparanhos-porto.pt/a-freguesia-info-censos).

In 2011, Paranhos had 44 298 inhabitants, 4 702 less inhabitants than in 2001. The population migratory movements may explain this fact. The population has tendency to choose the sectors in the periphery of Porto as an attempt to avoid the city centre confusion (Paranhos, 2012).

Consequence of having the biggest concentration of services, Paranhos is also the sector with the highest number of inhabitants. People have the tendency to stay in Paranhos as it allows them to stay near services like:

- Public Schools: kindergartens, Primary Schools, Basic Instruction, High-Schools, Universities (Faculdade de Ciências da Nutrição e Alimentação da Universidade do Porto, Faculdade de Desporto da Universidade do Porto, Faculdade de Economia da Universidade do Porto, Faculdade de Engenharia da Universidade do Porto, Faculdade de Medicina da Universidade do Porto, Faculdade de Medicina Dentária da Universidade do Porto, Faculdade de Psicologia e Ciências da Educação da Universidade do Porto) and Polytechnic Institutes (Instituto Superior de Engenharia, Instituto Superior de Contabilidade e Administração, Escola Superior de Educação) and others as Escola Superior de Enfermagem do Porto);

- ❖ Private Schools: kindergartens, Primary schools, Basic Instruction, High-Schools, Universities (Universidade Portucalense Infante D. Henrique, Universidade Católica Portuguesa, Universidade Fernando Pessoa, Universidade Lusíada do Porto);
- ❖ Research Centres (Centro de Investigação Médica da Faculdade de Medicina do Porto, Instituto Português de Oncologia do Porto, Faculdade de Engenharia do Porto; Centro de Estudos da Construção, Centro de Estudos de Energia Eólica e Escoamentos Atmosféricos, Centro de Estudos de Fenómenos de Transporte, Centro de Investigação do Território, Transporte e Ambiente, Centro de Investigação em Geo-Ambiente e Recursos,…);
- ❖ Hospitals (Hospital de São João, Instituto Português de Oncologia do Porto, Centro Hospitalar Conde Ferreira);
- ❖ Clinics (from several medical specialties);
- ❖ Veterinary hospitals;
- ❖ Veterinary Clinics;
- ❖ Firefighters Stations;
- ❖ Underground private parks;
- ❖ Subway stations.

2.1 Brief history of Porto

2.1.1 Introduction

Paranhos is one of the sector of Porto city. Located in the right border of Douro River, on NW of Portugal, it is one of the most ancient cities of all Europe. Porto's history dates back at century VI. The conquest of Portucale occurred in 868 AC; this was the first name of Porto region and it is considered one of the most important events of old Porto history. After 868 A.C., Porto became the centre of the Christian conquering movement at Iberian Peninsula. Porto was one of the most important cities since XII century. It has been developing itself through granitic scarp of Douro River. The historical zone of Porto and its architectural and historical spoil was recognized by UNESCO as world patrimony, in 1996 (Afonso, et al., 2007; Afonso, et al., 2009; UNESCO, 2013).

The name Paranhos appeared documented for the first time in 1689. Before the formation of the Portuguese County, Paranhos borough already existed; its inhabitants were Arabian people ("*mouros")* that remained in this region until the X century. Between the years of 1123 and 1341, two-thirds of the borough belong to the Church Lords of Sé do Porto.

As the most of the boroughs, Paranhos was growing along its church, which was built by rich farmers also in X century.

The evolution of the gowning number of inhabitants in Paranhos is showed in Figure 13.

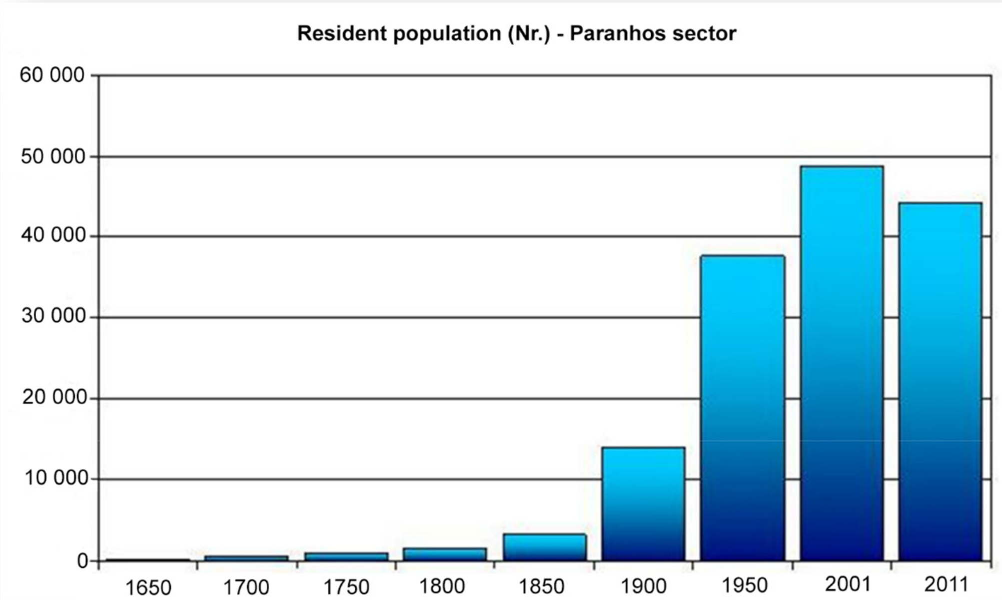


Figure 13. Evolution of Paranhos population through the years. Adapted from: (http://www.jfparanhos-porto.pt/a-freguesia-info-censos).

Only in 1837, Paranhos was integrated in Porto city; until this moment, it belonged to Maia. Paranhos image is also very associated to its greater and important green space: Quinta do Covelo (JFParanhos, 2006; Paranhos, 2012; Freitas, 2013).

2.2 Infrastructures

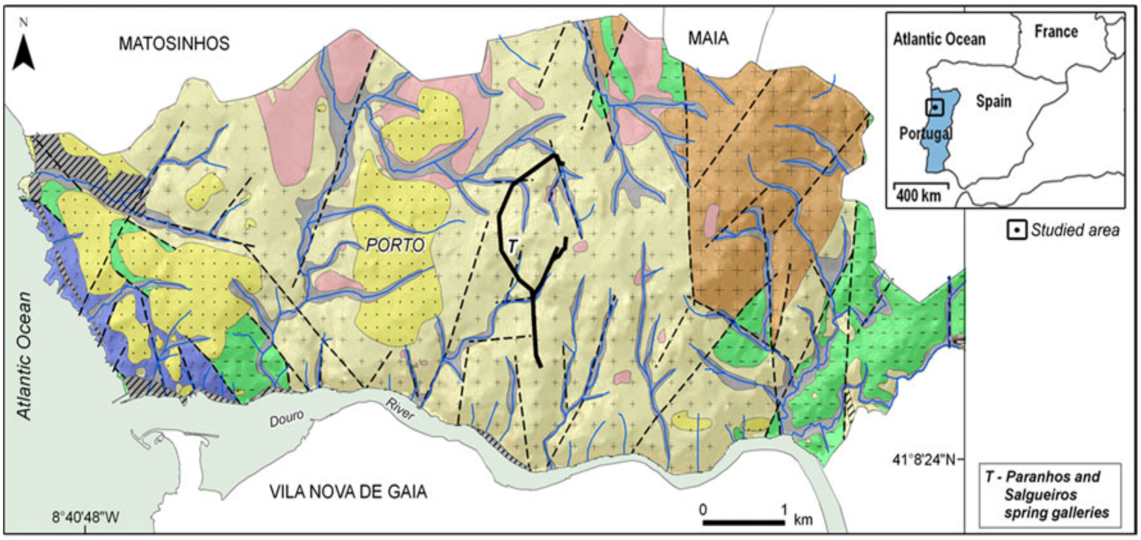
The expansion of infrastructures and the opening of new fronts of urbanization in Porto city made possible a high growth of residential offer in the second half of the 90’s. This period was characterised by a high rate of construction. In 2004 Porto metropolitan area counted with more 220 951 groups of buildings than in 1994 (Oliveira, et al., 2006). Alongside, other structures as Via de Cintura Interna (VCI) and Circunvalação appeared to allow the communication of Paranhos sector with other areas.

In Porto there are 60 springs, fountains or mines, between Salgueiros and Fontainhas, however the ones in Arca D’Água (Paranhos) are the most abundant. Several tunnels were built in Porto city for water distribution. Paranhos inhabitants and the habitants from other boroughs do not drink that water since XIX century. Despite the water cannot be consumed, it could be used for other daily tasks such as washing the streets and/or irrigate gardens.

The City Council of Porto has recently opened the underground spring of Arca D’Água Garden to the public. The underground spring is considered one hidden treasure of Paranhos and therefore, a hidden treasure of Porto (Quaresma, et al., 2011).

2.3 Regional geological framework (Paranhos sector)

Porto is located in a complex geotectonic domain of the Iberian Massif (MI), adjacent to the Atlantic Ocean (Ribeiro, et al., 1990; Pereira et al., 2010; Pereira & Neves, 2012). Porto region is placed between the Douro-Carboniferous Through and Porto-Coimbra-Tomar shear zone (Figure 14) (Chaminé, et al., 2003). The geomorphology of Porto consists of a planar littoral platform dipping gently to the west and culminating around 120 metres above the sea level. To the east, the surface is bounded by series of ridges ranging from 250 to 300 meters above the sea level. The flatness of this morphological surface is interrupted by incised river valleys, particularly Douro river valley that is tectonically controlled.



Regional Hydrogeological Groups	Hydrogeological Units		HYDROGEOLOGICAL FEATURES: Connectivity to the drainage network			Type of flow		Weathering				More suitable exploitation structures	
			with	without	possible	porous medium	fissured medium	low thickness	high thickness	clayey	sandy	dug-wells, galleries and springs	boreholes
Sedimentary cover	alluvia (ancient waste disposal, wd)	wd	x			x		n. a.	n. a.	n. a.	n. a.	x	
	sands and gravels		x			x		n. a.	n. a.	n. a.	n. a.	x	
Metasedimentary rocks	micaschists, schists and graywackes				x		x		x	x			x
Granitic rocks and gneisses	granite, medium to coarse grained, with K-feldspar megacrystals				x		x	x	x		x	x	x
	granite, medium to fine grained, with saprolite (sp) extensions	sp			x		x		x	x	x	x	x
	gneisses				x		x	x	x		x	x	x

n.a. = not applicable

Figure 14. Regional hydrogeological setting from Porto city (Afonso, et al., 2009).

The regional geotectonical framework of Porto urban area (Sharpe, 1849; Costa, 1958; Chaminé, et al., 2003) comprises a crystalline-fissured basement complex, which is strong deformed Late Proterozoic/Palaeozoic, met sedimentary rocks and granites. The Porto granites consist of two-micas, coarse grained, and greyish in colour, changing to yellowish when weathered. Phyllites, black schist, garnetiferous quartzite, mica schist, migmatites mainly compose the substratum complex and gneisses, whereas the sedimentary cover rocks are dominated by post-Miocene alluvial and Quaternary marine deposits. The granite is weathered to different grades, from fresh rock to residual soil, showing highly variable conditions, resulting in arsenisation and kaolisation, which may reach depths of more than 100 m. The nature of the weathered Porto Granite and its extreme heterogeneity combines all the negative elements, which influence the ability to control the face support pressure and it turns impossible to predict the massif behaviour. *"The permeability of the rock mass depends on its weathering grade. In the less weathered rock the* *flow is primarily related to the fracture system, while in the more heavily weathered material, the ground behaves more like a porous medium. The highly variable permeability of the rock mass has resulted in a very complex ground water regime. Although the overall permeability is of the order of* 10^{-4} *cm/s or lower, it is considered that preferential drainage paths exist within the granite mass"* (Babendererde, et al., 2005).

The crystalline bedrock of Porto city consists of gneisses-micaschists in the western part and granites in the eastern part of the city. The boundary between these two major geological units is established by a major fault zone (Porto-Coimbra-Tomar shear zone, trending NNW-SSE). Variscan granitic rocks, representing the Porto granite faces and the Ermesinde porphyritic faces, underlie the Porto site. (Araújo, et al., 2003; Afonso, 2003; Afonso, et al., 2004; Afonso, et al., 2004; Afonso, et al., 2009; UNESCO, 2013).

Materials and Methods

3 Materials and Methods

3.1 Materials

For the radiometric survey were used two different equipments: a Scintillometer SPP2 NF, from SAPHYMO and a radiation detector, from GAMMA SCOUT® (GS-3).

The Scintillometer SPP2 measures gamma radiation in counts per second (cps) while GAMMA SCOUT® measures both: gamma (γ) and total ($\alpha + \beta + \gamma$) radiation, in cps, and gamma (γ) and total ($\alpha + \beta + \gamma$) doses of radiation, μSv/h. This equipment can also measure three types of radiation groups: $\alpha + \beta$;γ; $\alpha + \beta + \gamma$.

The Scintillometer SPP2 NF has an acoustic alert, which starts functioning when it detects very high concentration of radiation according to a limit established. The methodology followed with the SPP2 was to make two registration forms in the same site, at 1m to ground and close to it, five times each one. Then the average of the five measures was considered as the final value to further interpretation. The measures were made always with the same scale: 150 scale - direct reading; the readings values were later on adjusted to the right scale for further interpretation. The GAMMA SCOUT® (Figure 15) was used mainly to collect exposure dose rate at the same locations. This dosimeter measured the absorption dose allowing to establish a comparison term between the radiation values collected with both equipments. Therefore, these measurements were included in this study.

Figure 15. Radiation detector from GAMMA SCOUT® (GS-3).

For gamma radiation dose and total radiation dose were made two measurements at each site. The equipment stayed 10 minutes in each one. During the logging interval, the dosimeter collects several measurements, however from all the collected data it only presents the average of the totality of values collected.

The information remained in all the registration forms was filtered and organized in two tables. The data was used to make a first approach of what would be radiation cartography of Paranhos sector (c.p.s./µSv/h - depending on the device used), humidity (%) temperature (ºC) and atmosphere pressure (mm-Hg). The values from GS-3 related to radiation were not represented in maps. This information was used only to establish a relation between the devices, as it was already mentioned.

During this study, two different tools were used:

- Surfer 8, used to do all the statistical/geoestatistical data treatment;
- Geographical Information Systems (GIS), such as ArcGIS to generate maps with the distribution of radiation at Paranhos sector.

3.2 Methods

3.2.1 Sampling location

Places like public and private colleges (from kindergartens to universities), research centres, health care institutions (hospitals and clinics from several medical specialities), animal care institutions (veterinary hospitals and clinics, municipal kennel for dogs and cats, firefighters station and churches were chosen. Initially these were the kind of services selected to be part of the study. However, later on it was decided to study public or private underground services as subway stations and underground parking. Therefore, they were added to the Initial Sample Site some places that meet these requirements. The places that were considered important to be included in the study were compiled; to each location a numeric code was attributed.
The list is presented at Appendix 8.
Table 6Table 6 is not continuous because:

- Some of the places presents on the initial list were not interested in this study
- Some institutions did not respond to our request;

There were some institutions that response later and it was not possible to do the measurements. These sample sites were chosen due to the concentration of persons in the buildings during the day, attending always to the objectives of this study. The location of the measurements effectively carry out are represented in the following map with the limit of the borough Paranhos.

The markers represent all places measured, surface and underground (Figure 16). The complete list is represented in Appendix 1. The conversion table of radiation values from Scintillitometer is indicated in Appendix 8.

Table 6. Measurement sites.

Code number	Places	Measurement location	
		Surface	Underground
1	Bombeiros Sapadores do Porto	X	
2	Hospital São João	X	
3	Centro Hospitalar Conde Ferreira	X	
4	Instituto Português de Oncologia (IPO)	X	
5	Instituto de Patologia e Imunologia Molecular (IPATIMUP)	X	
6	Centro regional de Sangue no Porto	X	X
7	Hospital Veterinário do Porto	X	
8	Igreja de Amial (Nossa Senhora de Fátima)	X	
11	Igreja de Marquês (Senhora da Conceição)	X	
12	Igreja de Paranhos (São Veríssimo)	X	
14	Infantário Pom Pom	X	
15	Infantário o Principezinho Encantado	X	
16	Associação Surpresa do Bebé	X	
17	Infantário Nossa Senhora de Fátima	X	
18	Sorrisos Mimosos Clinica Dentária	X	
19	Infantário o Aprendiz	X	
20	Navegar no saber, centro de estudo	X	
22	Colégio Júlio Dinis	X	
23	Mestre do saber, centro de estudos	X	
24	Infantário Nossa Senhora da Conceição	X	
25	Clinica Veterinária Arca d'Água	X	
26	Colégio Luso-Francês	X	X
27	Infantário o Popas	X	
28	Escola EB1 do Covelo	X	
29	Escola EB1 São Tomé	X	
30	Escola EB1 Professor Augusto Lessa	X	
31	Escola EB1 Costa Cabral	X	
34	Externato Perpétuo Socorro	X	
36	Garden in front of Escola EB1 da Azenha	X	
37	Obra Diocesana Promoção Social	X	
38	Túneis de Arca d'Água		X
43	Escola EB2/3 Areosa	X	
44	Escola EB2/3 Paranhos	X	
46	Escola Secundária António Nobre	X	
47	Escola Secundária Filipa de Vilhena	X	
48	Faculdade de Desporto UP	X	

(Table 4 resumption)

49	Praça Velasques	X	
50	Faculdade de Economia da UP	X	
51	Faculdade de Engenharia da UP	X	
52	Faculdade de Medicina/Centro de Investigação Médica da UP	X	
53	Faculdade de Medicina Dentária da UP	X	
54	Faculdade de Psicologia e Ciências da Educação UP	X	
55	Escola Superior de Educação	X	
56	Escola Superior de Enfermagem São João	X	
57	Instituto Superior de Engenharia do Porto, ISEP	X	
58	Universidade Católica Portuguesa	X	
60	Universidade Portucalense Infante D. Henrique, UPT	X	
61	Underground Station – Salgueiros		X
62	Underground Station – Pólo Universitário		X
63	Underground Station – Marquês		X
64	Underground Park - C.C.Campus		X
65	Underground Park – UPT		X
66	Underground Park – Braga Parks		X
67	Underground Park – ISEP		X
68	Instituto Politécnico do Porto	X	
69	Underground Park – FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO		X
70	Clinica Veterinária Francisco d'Assis	X	
71	Underground Station – Combatentes		X
72	c.c. Campus São João	X	
73	Central de Enfermagem do Porto	X	
74	Labmed	X	
75	Clinica MédicoDentária	X	
76	Hospital Veterinário Montenegro	X	
77	Escola Básica Montebello	X	
78	Escola Nicolau Nasoni	X	
79	Clinica Veterinária da Areosa	X	
80	Quinta do Covelo	X	
81	E.S. Cenáculo	X	
82	Private building in Serpa Pinto street, 495	X	
83	Garage in Serpa Pinto street, 460		X
84	Dragon Force, Vitalis Park	X	
85	Escola Básica das Antas	X	
86	Escola Básica Monte Aventino	X	
87	Private building in Serpa Pinto street, 776	X	
88	Continental Garage	X	
89	Jardins Escola João de Deus	X	
90	Arca de Água Garden	X	
91	Colégio do Amial	X	
92	Quinta	X	
93	Music academy of Costa Cabral	X	

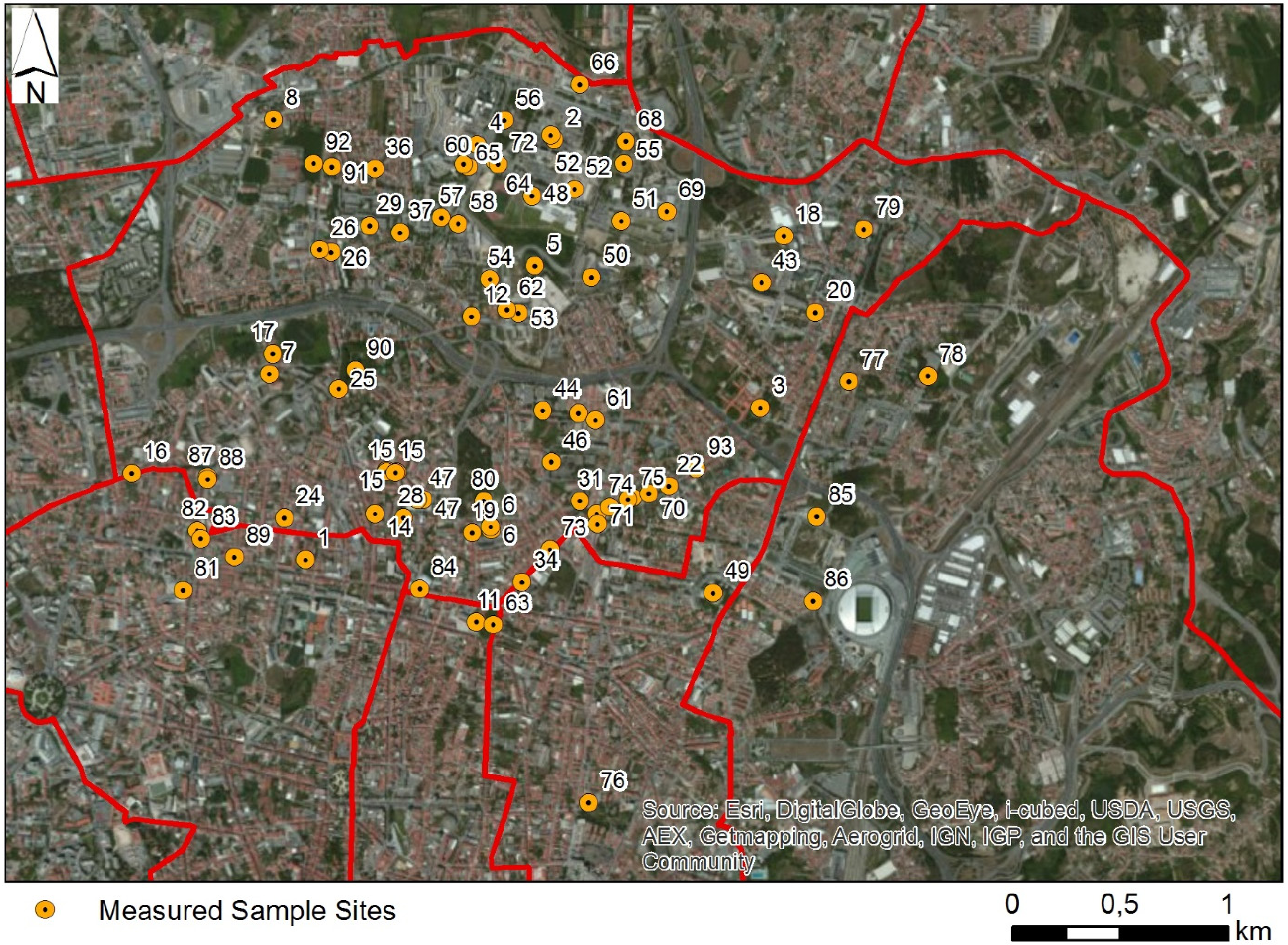


Figure 16. Measurement sites.

3.2.1.1 Challenges in measurement processes

At this stage it is important to know about the difficulties in this process.

The second phase started as soon as the list and respective geographic representation was ready: to contact all the places asking for permission to start the study. This first contact involved in a meeting with the responsible of the institution to explain the study and presentation of a document from the Instituto Superior de Engenharia do Porto (ISEP) asking for permission. This approach was made in person. However, when the responsible was not present it was by phone call and e-mail; sometimes by both ways: personally and e-mail when the respective responsible thought it was necessary.

The first reaction of the majority of the persons in charge was too deny the study, saying they were not interested. It is important to refer that the major part of people with whom there was a contact has no high education, and sometimes this fact is associated to the lack of information that can generate fear and refutation. In addition, the fears of possible consequences of the study were the primary thoughts, which make them show no interest on it.

Despite the initial negative answers, some of them asked for a second meeting and made questions as:

"What is the final objective of this study?"

"Why this institution and not another one?"

"May I see the results before the thesis is ready?"

"May you tell me the results just for information?"

These questions allied to the first reaction show that most people do not have an open mind for academic studies. Their concern is not to make the study to see if it is necessary some kind of correction to protect the people who enjoy the institution as the case of children in kindergartens.

However, there are some institutes as IPO or Borough Council of Paranhos, which at the beginning showed interest and availability to do the study and asked for a formal request by e-mail. When the e-mail was sent, they emitted a negative answer saying that they were not interested.

Most of private and public kindergarten, primary schools and high schools that authorized the measurements had only one request: to make the measurements when there were no children or young people in the places. Being so, they granted some empty rooms or asked to do the study during class time.

This experience taught us that it is necessary to educate our society about daily problems as for example, the exposure to radiation in daily tasks, in and out of buildings. For sure if they know the risks and possible health effects caused by long time exposure to low doses of radiation they would be more receptive in future studies from the same area.

3.2.2 General Datasheet

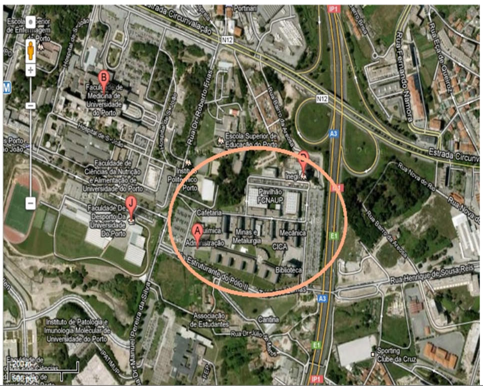
One of the primary tasks was to elaborate two registration forms where all the data collected at the sample sites with both equipments were noted.

This registration form must accomplish the following items:

- Map of the sample site;
- Picture of the measured place;
- Date, hour, place number (numeric code attributed to every site), description (if it was necessary);
- Type of measurement: underground or surface; in this case if it was indoor or outdoor;
- Type of construction material (granitic rock, sedimentary rock, metamorphic rock, brick, cement, concrete, asphalt, tiles, linoleum, wood and dirt): each construction material also has a numeric code to render easy the measurement process. The primary objective in collecting this kind of information was to elaborate a statistic analysis to conclude if there is any relation between the construction material and the concentration of radiation in each site;
- General data as humidity (%), temperature (^{0}C), wind direction, atmosphere pressure (mm-Hg) and wind speed (m/s). This data was taken to see if there was some kind of relation among the radiation measured and each one of these parameters;
- Gamma radiation measurements: five measurements were made at each location both close to the ground and at one meter of the ground; making a total of 10 measurements in each location;
- Average of the gamma radiation measurements alongside with minimum, maximum and standard deviation.

The registration form elaborated for Scintillometer SPP2 measurements (Figure 17) includes almost the same parameters presented at the registration form of GS-3 measurements (Figure 18). The differences lay on the kind of measurement and on the general data collected.

Radioactive units used, legal limits and units conversion are include in Appendix 2 and Appendix 3 respectively. Both registration forms are presented in the following pages. All the registration forms of Scintillometer SPP2 measurements and the ones from GS-3 are indicated in Appendix 4 and Appendix 5.



Date: 24/07/2012	**Hour:** 8h20min	**Place Number:** 51	**Description:** Classroom F204, Mining department museum

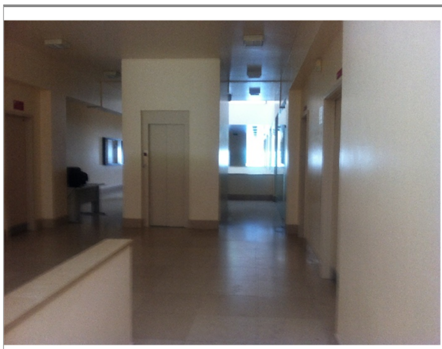
Measurement:	Underground	Surface	
Measuring site:		Indoor	Outdoor

Type of material	Legend:							
	Igneous Rock	1	Brick	4	Asphalt	7	Wood	10
	Sedim. Rock	2	Cement	5	Cotto	8	Dirt	11
6	Metam. Rock	3	Concrete	6	Linoleum	9		

General Data					
Humidity, %	94	Temperature, ºC	17	Wind Direction	NE
Atmosphere Pressure, mm	754	Wind Speed, m/s	1,94		

Measuring the gamma radiation, c/s		
Measuring number	One meter of soil	Close to the Ground
1	150	150
2	135	135
3	450	450
4	1350	850
5	1000	1000
Average/(min-máx)/StdDev	671/(150-1350)/482,14	517/(150-1000)/354,76

Figure 17: Registration form for the Scintillometre SPP2 NF.

Date:	15/04/2013	Measure time:	10 Minutes	Place Number: 57

Measurement:	Underground	Surface

Type of material	Legend:							
	Igneous Rock	1	Brick	4	Asphalt	7	Wood	10
	Sedim. Rock	2	Cement	5	Tiles	8	Dirt	11
3	Metam. Rock	3	Concrete	6	Linoleum	9		

General Data					
Humidity, %	77	Temperature, ºC	15	Description:	

Measuring the gamma radiation, µSv/h		
Measuring time	Surface	Underground
Gamma Radiation: 11h49	0,5	
Total Radiation: 11h59	0,7	

Figure 18: Registration form for the GAMMA SCOUT®.

3.2.3 Statistical analysis

Natural radiation from rocks and soils is generated by the decay of radioactive elements such as potassium (K^{40}), uranium (U^{238}), and thorium (Th^{232}). The radioactive decay of these elements results in the emission of gamma rays with enough intensity to penetrate into the human body.

The selected equipments were used to obtain different information concerning to the same location. Therefore, the resulting of two measurements were classified as direct measurements and indirect measurements. Direct measures are the ones that give us the radiation content through the measurement process. Indirect measures allow us to know the dose rate, however, to know the radiation content we need to establish some relations.

Gama radiation values were measured with SPP2 and total gamma radiation values as well as radiation doses were measured with GAMMA SCOUT®.

The collected data was organized and submitted to a basic statistical analysis. Resulting in general statistical parameters such as mean, median, standard deviation, minimum, maximum and N (number of times that each kind of measurement was performed).

After that, all the collected data was inserted into Surfer 8 software for a geostatistical study and generate the necessary grids to represent the gamma radiation values and doses rates:

- Gamma radiation, direct measurements, at 1 m to ground and close to ground for each situation: indoor, outdoor and underground (whenever it is possible);
- Total and gamma radiation dose, indirect measures, at surface (indoor and outdoor) and underground.

We also have mapped standard deviation, only for direct measures. With this kind of maps we pretend to see if the areas with higher uncertain correspond to those with higher interpolated values; sustaining the variability of the collected data.

To complement the information of the study meteorological parameters such as humidity, temperature and atmospheric pressure were also mapped representing their variation in the borough of Paranhos. Both maps were overlaid and displayed to analyse a possible relation between radiation and dose rates collected outdoor with the meteorological parameters.

In Figure 19 is presented a diagram with the measurements location and the type of collected data.

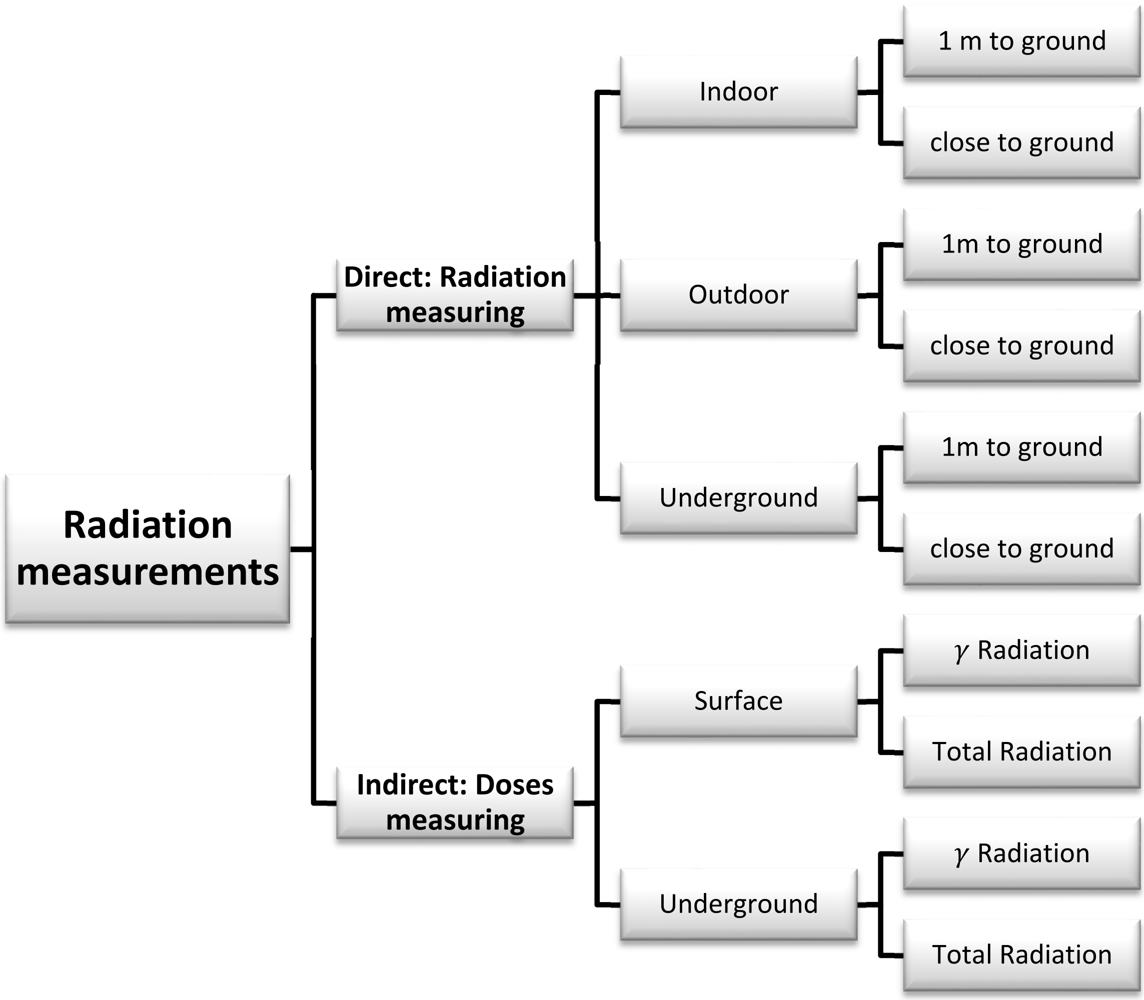


Figure 19. Representation of all subcategories at radiation measurements.

Five case studies were considered: three from direct measures and two of indirect measures (Figure 20):

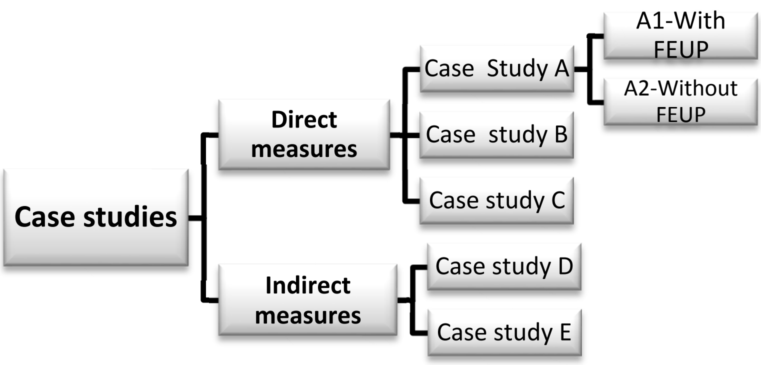


Figure 20. Case studies.

The collected data was organized according to type of equipment used.

Case study A (indoor) has one more subdivision attending to the fact that the measurements were carried out at Faculdade de Engenharia da Universidade do Porto mineral's museum and they reflect the influence of mineral samples with uranium resulting into a huge “hot spot”. Because of this, another case study was considered without the measurements in this location as the values are perfectly justified by the samples.

The three case studies from direct measures (gamma radiation measurements) A, B (outdoor) and C (underground) were both analysed at 1m to ground and Close to ground. For these three cases, the standard deviation was represented in maps only for the measurements carried out at 1m from the ground.

Case studies D (surface) and E (underground) have also two analysis: total radiation dose rate and gamma radiation dose rate.

Important:

Some measurements were repeated to confirm the first values collected.

In the case of Scintillometer SPP2 this repetition was made at Campus São João. The device turn on its acoustic alert, warning us for high values of radiation inside the building over 50 000 cps. The values that SPP2 was detecting were so high that it did not have scale to show its value. After a week, the measurement was repeated and this phenomenon did not repeat itself. This could be explained by the cancer patients that are under radiation treatments. Their bodies emit high quantities of radiation until three days after the treatment (durability of radioisotopes used in this kind of treatments). This fact could occur in the airports; normally the patients have a statement from the hospital or the doctor attesting the radiological treatments (Sisson, et al., 2011).

At some sampling site GS-3 registration formed higher gamma radiation doses than total radiation. This fact was not expectable. Therefore, the measurements were repeated in two sites: ISEP underground parking and FMUP Investigation Centre. The phenomenon happened again; this could be due to a previous overflow of the device.

3.2.3.1 Fundamentals of geostatistics

The objective of a geostatistical analysis technique is the analysis of spatial continuity. To characterise and quantify how spatially disperse the characteristics of parameters with spatial relations. In this case, the parameters to be represented will be gamma radiation, gamma radiation doses and total radiation doses.

Kriging is a regression method used to interpolate data, based on the principle that nearby points in space tend to have similar values.

The first step of the estimated process is the calculation of a variogram for multiple values of h (distance between sample sites) in space. The collected data was used to map the dispersion of the gamma radiation along the studied area. The dispersion was estimated using geostatistical kriging, which is a linear estimator most widely used nowadays in geostatistics to calculate values in non-sampled locations. It was checked that in all cases there was anisotropy ($r > 1$) with a different continuity direction for each case.

The software Surfer 8 was used as a tool for the geostatistical kriging and the results were displayed in maps using the software ArcGis. For each map it was generated a variogram based on a spherical model fit.

Results and discussion

4 Results and discussion

4.1 Data analysis: direct radiation measurements

The obtained data is represented in Table 7. The highest mean value corresponds to the case study C, which is a measurement in underground environment taken close to ground, **243** cps. Case study C has registration formed values ranging between **44** and **900** cps; measurements carried out at 1 meter to ground. Being **900** cps the highest value of all. The case study A, without Faculdade de Engenharia da Universidade do Porto measurements, presents the lowest mean value **125** cps registration formed at 1 m from the ground.

Table 7. Basic data statistics.

Location		Mean (cps)	Median (cps)	Std. (cps)	Min. (cps)	Max. (cps)	N
Case study A-Indoor	1 m to ground	132	125	64	50	617	74
	Close to ground	132	125	56	41	517	74
	1 m to ground without FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO	125	124	30	50	193	73
	Close to ground without FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO	127	123	33	41	194	73
Case study B-Outdoor	1 m to ground	144	138	45	50	400	60
	Close to ground	149	146	40	50	238	59
Case study C-Underground	1 m to ground	231	150	221	44	900	21
	Close to ground	243	158	212	47	750	22

The indoor value in the Faculdade de Engenharia da Universidade do Porto (case study A) has a very high indoor value when compared with the analysis without Faculdade de Engenharia da Universidade do Porto constitutes an abnormality. This measurement was made intentionally in the Mineralogy Museum of the Mining Engineering Department with the purpose to obtain a hot spot, which was caused by the uranium minerals present in several samples. Since this data can bias the geostatistical models, it was considered two sets of data in case of study A: the first one with all the data and the second one excluding the abnormality, case study A2. The data referring to the direct measurements is included in Appendix 6.

4.1.1 Spatial analysis of gamma radiation data

A spatial analysis was performed with Surfer 8. Variograms were generated and adjusted to a spherical model. In the next figures (Figure 21, Figure 22 and Figure 23) are presented the variograms for each case study.

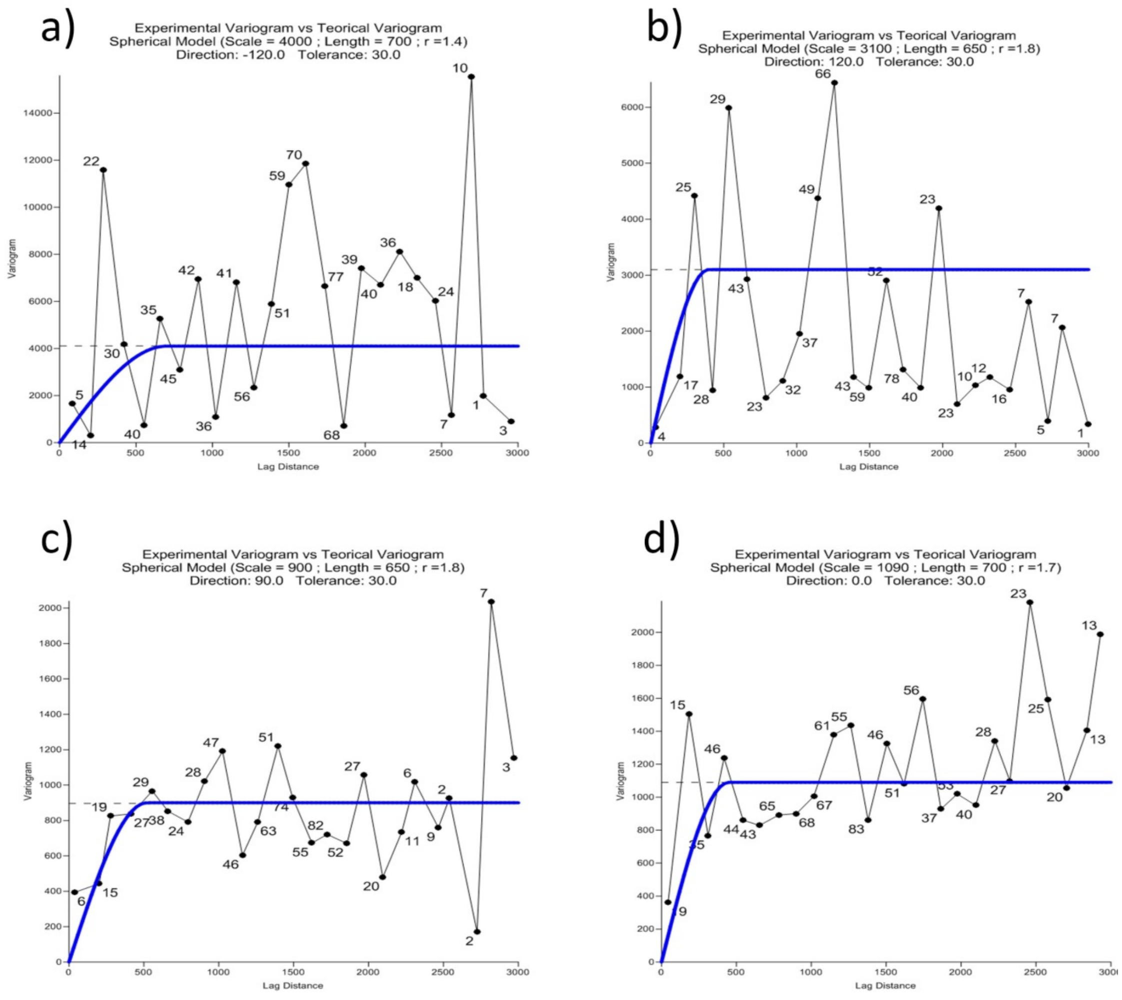


Figure 21. Case study A – a) indoor: 1m to ground, b) indoor: close to ground c) without Faculdade de Engenharia do Porto: 1m to ground and d) without Faculdade de Engenharia da Universidade do Porto: close to ground.

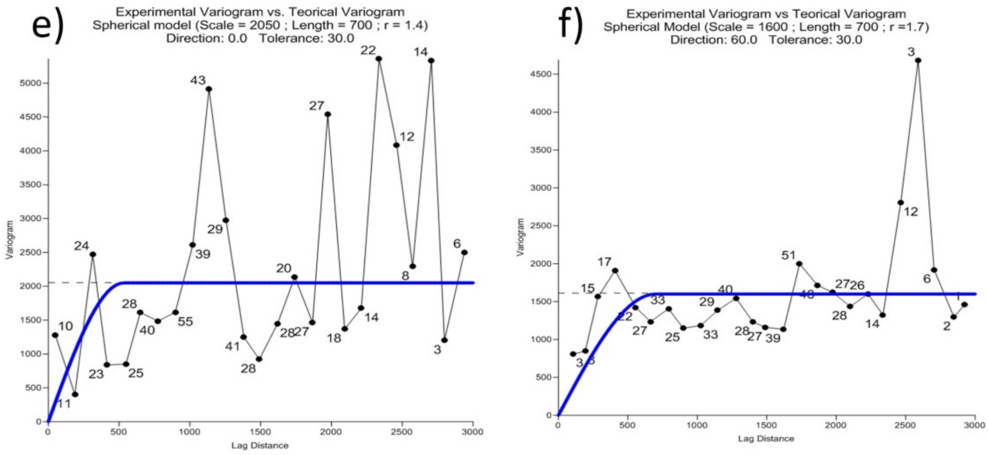


Figure 22. Case study B – e) outdoor: 1m to ground and f) outdoor: close to ground).

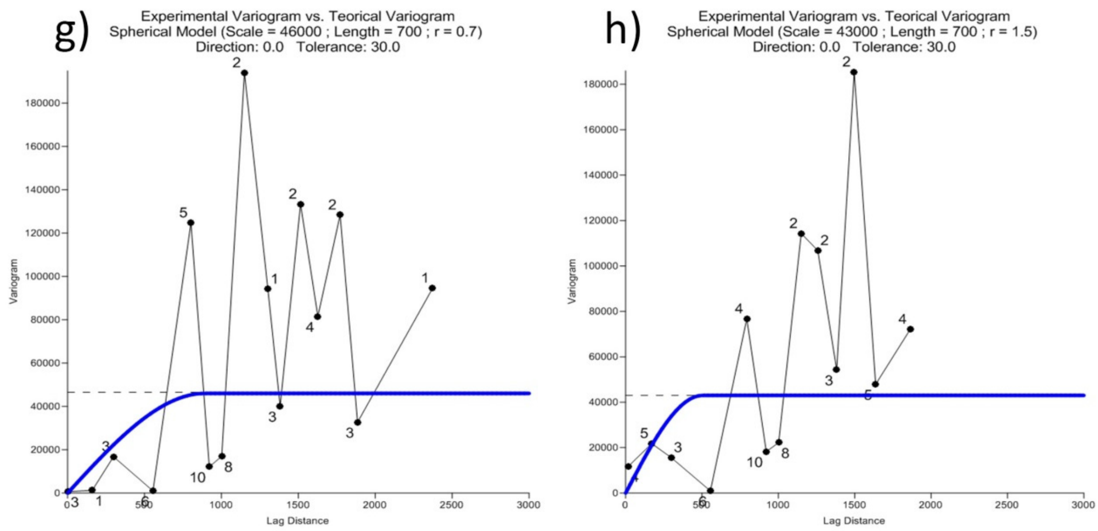


Figure 23. Case study C – g) outdoor: 1m to ground and h) outdoor: close to ground).

Case study A and B are the ones that better fit into the chosen model. The number of the values from the case study C is not enough for a good fitting to a spherical model or any other model.

4.1.2 Geographic analysis of the collected data from total gamma radiation

Based on the fitted theoretical variogram, several maps were obtained to represent the dispersion of gamma radiation values. The maps of each case of study and a brief descriptive analysis are presented in the following figures.

Case study A: A1

On Figure 24 it is possible to have notice that the gamma radiation indoor at 1 m to ground varies from **20** to **620** cps. The maximum, red area, was measured at Faculdade de Engenharia da Universidade do Porto Museum of Mining Engineering Department (I). This value was measured as a target as mentioned before, due to the presence of uranium minerals.

The sites B, C and D have all the same lowest value: **50** cps (II).

B was measured at Clínica Veterinária da Areosa, C at Escola Básica Montebello and D at FMDUP. These minimums could have several explanations such as the construction materials, the type of construction, among others.

On Figure 25 values vary between **30** and **520** cps (III) and represent the maximum values registration formed; it was also measured at Faculdade de Engenharia da Universidade do Porto, attending to the described before. Although IV is representing the lowest value, it was also measured at Clinica Veterinária da Areosa. These minimums could have several origins as construction materials, attending that the material can emit naturally radiation or it could absorb radiation emitting it after. The origin of these values can also be related to construction, the ground having granite in its constitution, among others.

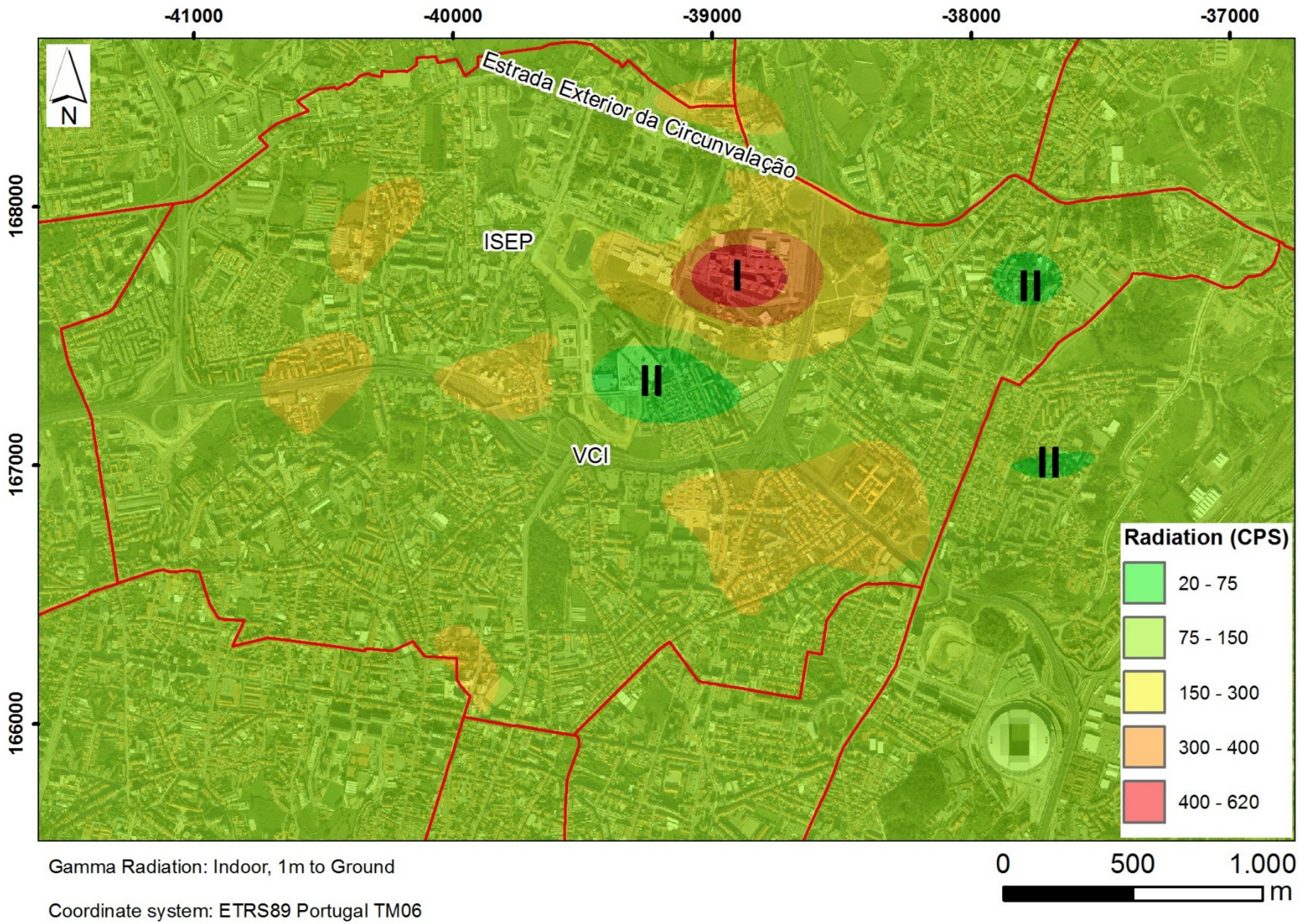


Figure 24. Indoor: 1m to ground total gamma radiation measurements.

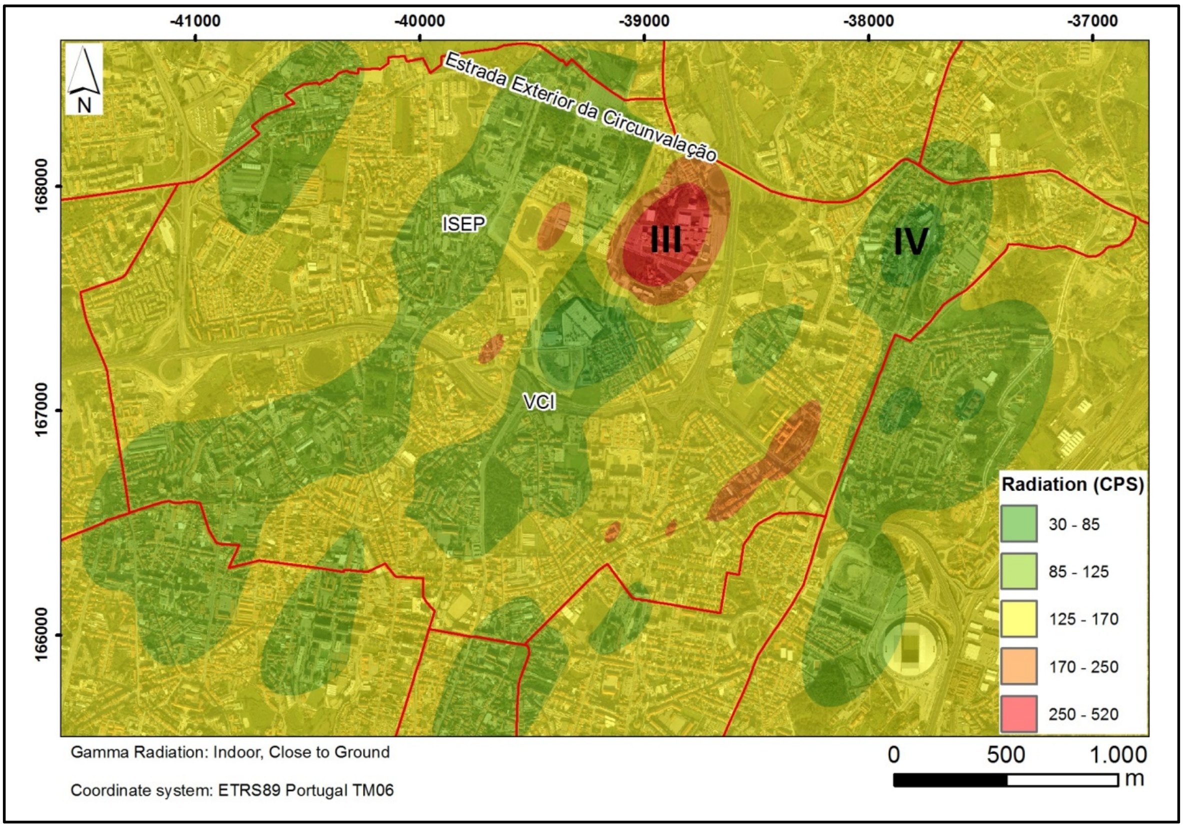


Figure 25. Indoor: close to ground total gamma radiation measurements.

As it can be seen in Figure 24 and Figure 25, both maximums I and III belong to the same area. As it was referred before the Mining Engineering Department of Faculdade de Engenharia da Universidade do Porto was measured because it was already known, it would influence the rest of values. It was also possible to observe that total gamma radiation level is higher Close to the Ground than at 1m to ground. Therefore, maps were also made without Faculdade de Engenharia da Universidade do Porto.

In the direct measurements, the spatial distribution of standard deviation was also analysed, however this analysis was only for maps at 1m to ground.

With the map represented in Figure 26 can be seen that the red area, the area with higher uncertain is coincident with the red area in Figure 24, area with higher interpolated values.

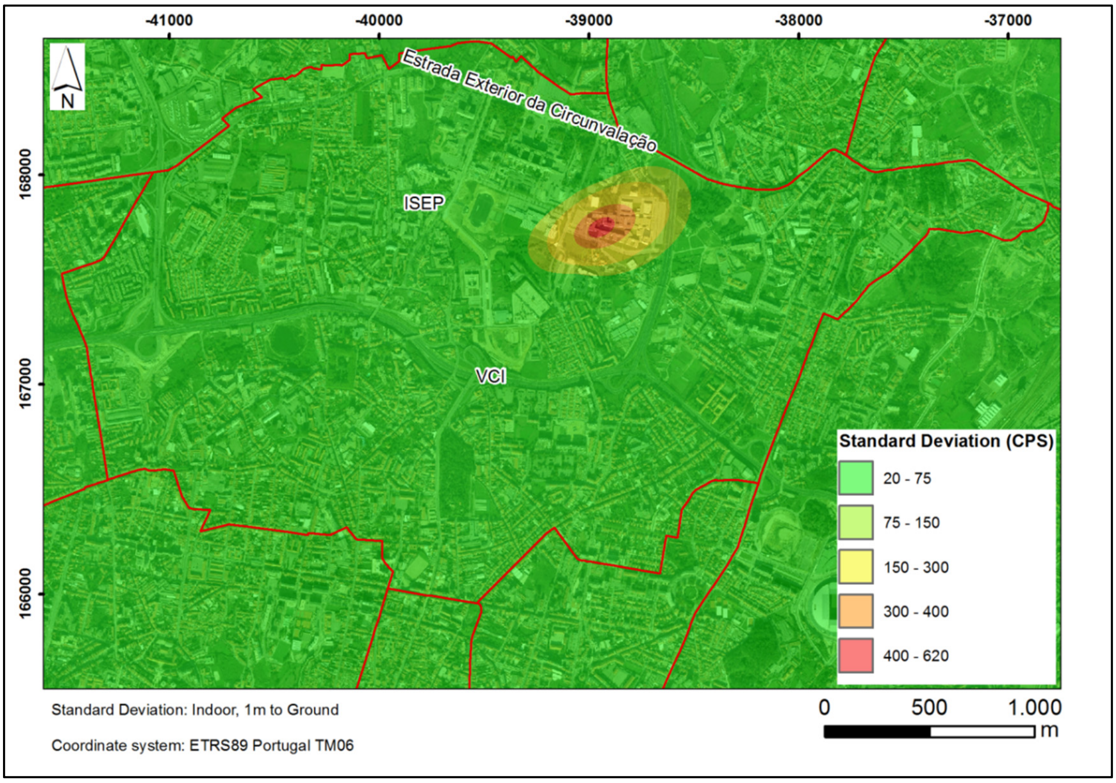


Figure 26. Indoor: 1m to ground standard deviation spatial distribution.

Case study A: A2

The map represented in Figure 27 was elaborated without Faculdade de Engenharia da Universidade do Porto values; therefore, the distribution varies between **50** and **190** cps. The highest value was measured at Centro Hospitalar Conde Ferreira (V). The construction material of this institution is predominantly Igneous Rock (granite), and this could be the reason why this sample site presents one of the highest registration formed values. The two minimums are coincident with the ones from Figure 24.

On Figure 28 the distribution values ranges between **40** and **195** cps. The maximum value was measured at FADEUP (VIII) and once more, the construction material present is made by igneous rock (granite); as it is known granite can be a radiation emitter, depending on the associated minerals, therefore it could be the cause of this value.

The maximums values identified as V and VIII are not in coincident areas; however, the minimums values identified as VI and IX are not very far away.

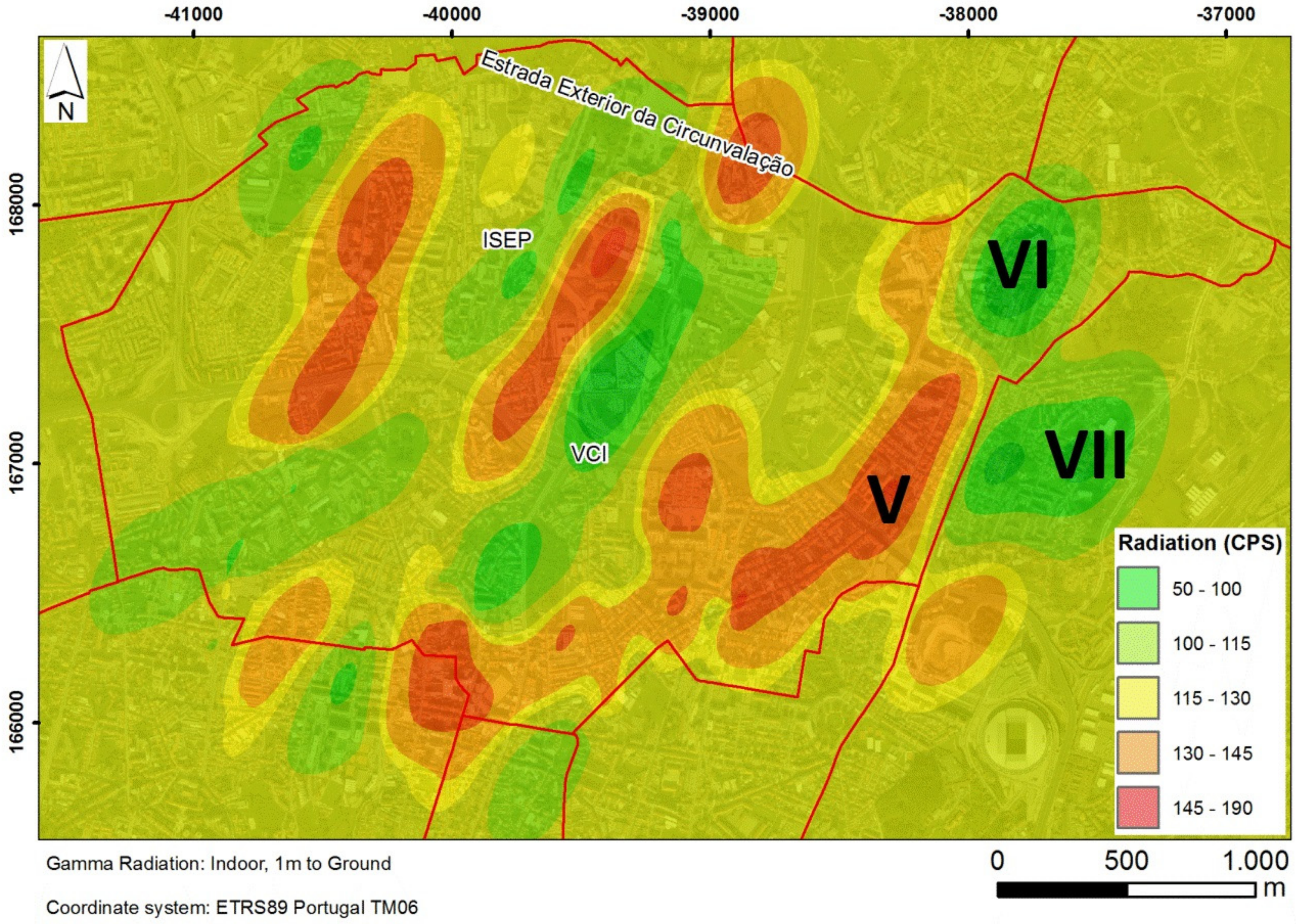


Figure 27. Indoor: 1m to ground total gamma radiation measurements, without Faculdade de Engenharia da Universidade do Porto.

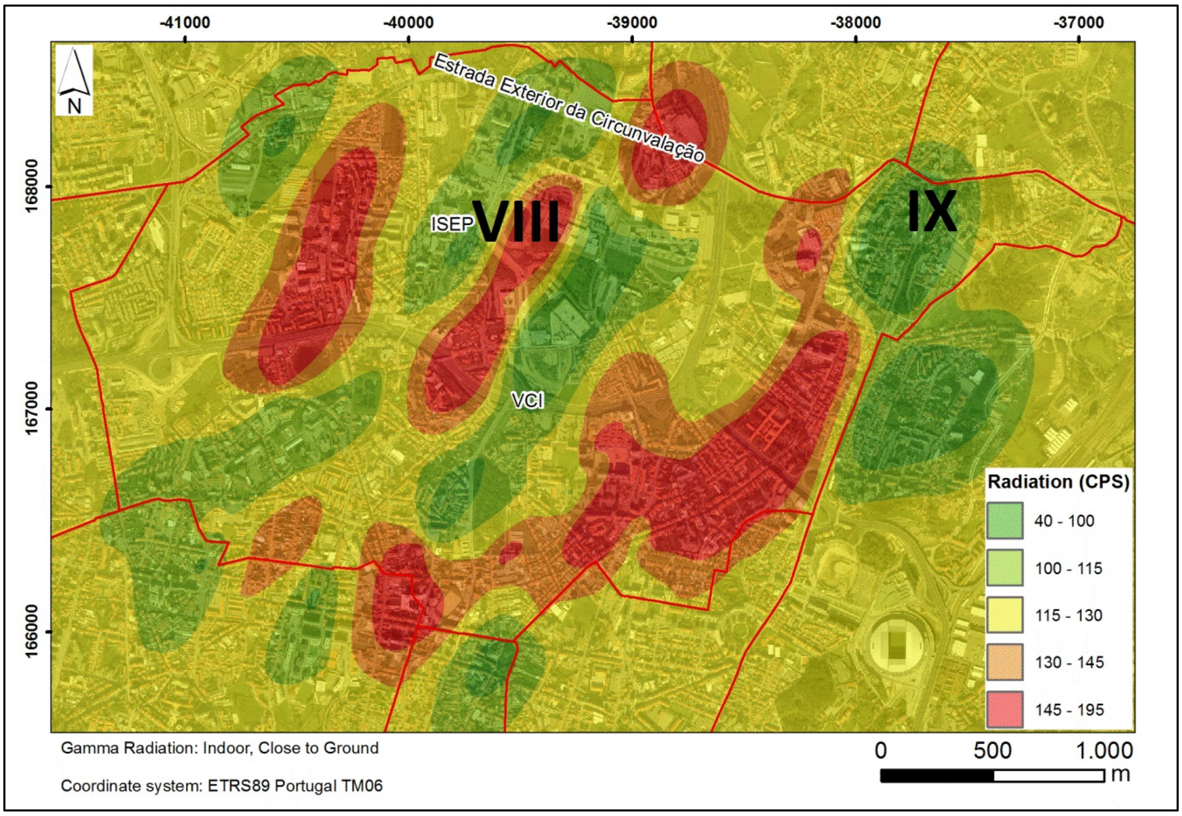


Figure 28. Indoor: close to ground total gamma radiation measurements, without Faculdade de Engenharia da Universidade do Porto.

Comparing case study A1 and case study A2 we can conclude that, in general, there are coincident areas. This means that areas with higher values, both at 1m to ground and Close to ground seem similar and this pattern repeats with minimums. Both maps representing indoor close to ground measures (Figure 25 and Figure 28) present higher levels of the total gamma radiation. This fact could have origin in the ground formation; higher quantities of granite in soil could be the reason to cause this phenomenon.

The spatial distribution of the standard deviation was also analysed in direct measurements but only for maps referring to measurements registration formed at 1m to ground. With the map represented in Figure 29 it can be seen that the red area, area with higher uncertainty, is coincident with the red area in Figure 27, area with higher interpolated values.

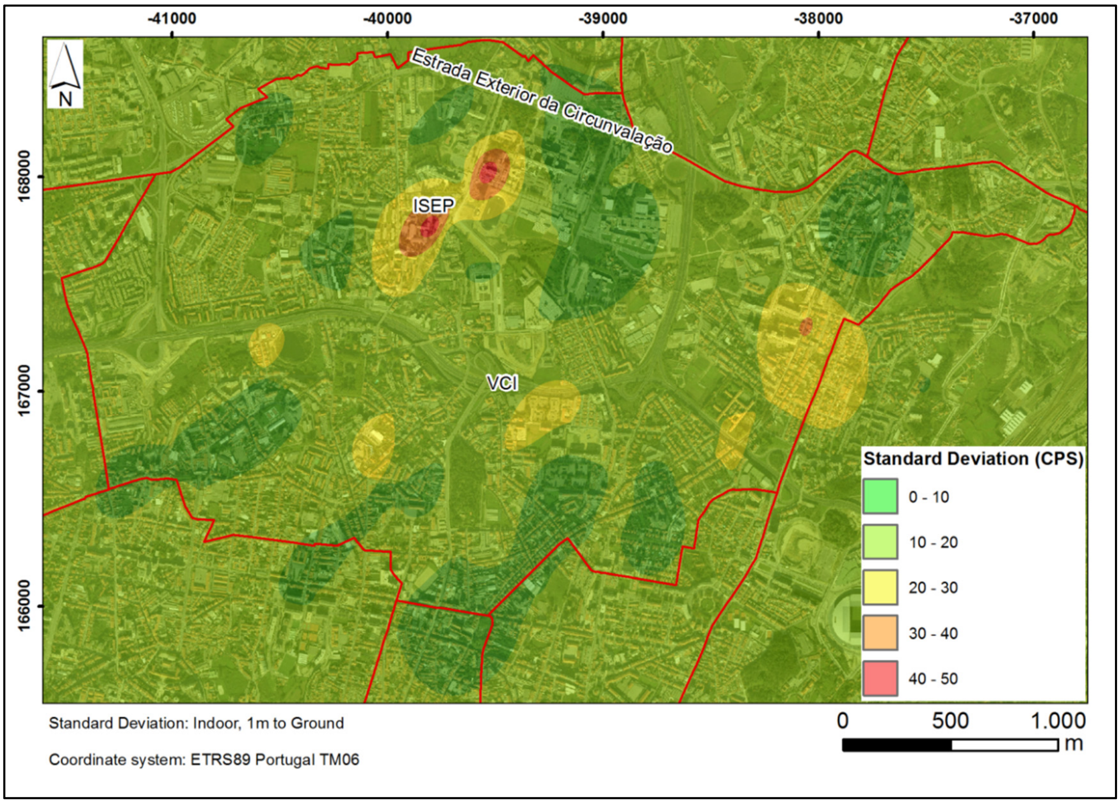


Figure 29. Indoor: 1m to ground standard deviation spatial distribution without Faculdade de Engenharia da Universidade do Porto.

Case study B

On Figure 30 values range between **50** and **450** cps. The maximum, marked in the red area with X, was measured at the entrance of Mananciais do Porto in Arca d'Água. These values could be related with the presence of evansite (uranium mineral) that emits total gamma radiation.

The minimum represented in the above figure is coincident with the minimum in all figures presented before, even in those that have more than one minimum.

On Figure 31 the distribution values varies from **50** to **450** cps. The maximum was measured at Colégio do Amial (XII). The construction material present at this sample site is asphalt. The minimum area is coincident with the one of the minimum areas from Case of study A.

Despite the similar distribution, the map from Figure 31, Close to the Ground measures have higher values of total gamma radiation.

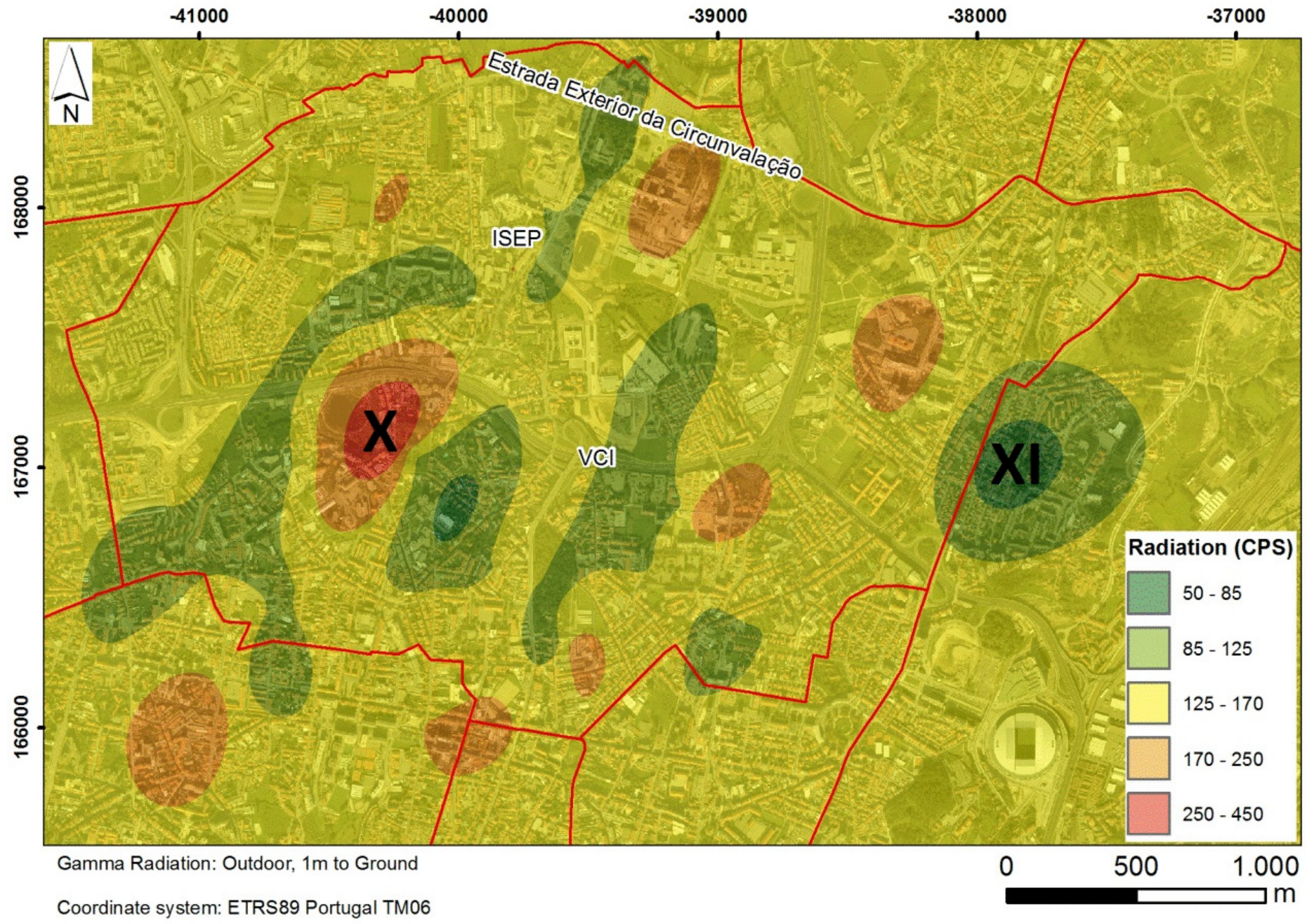


Figure 30. Outdoor: 1m to ground total gamma radiation measurements.

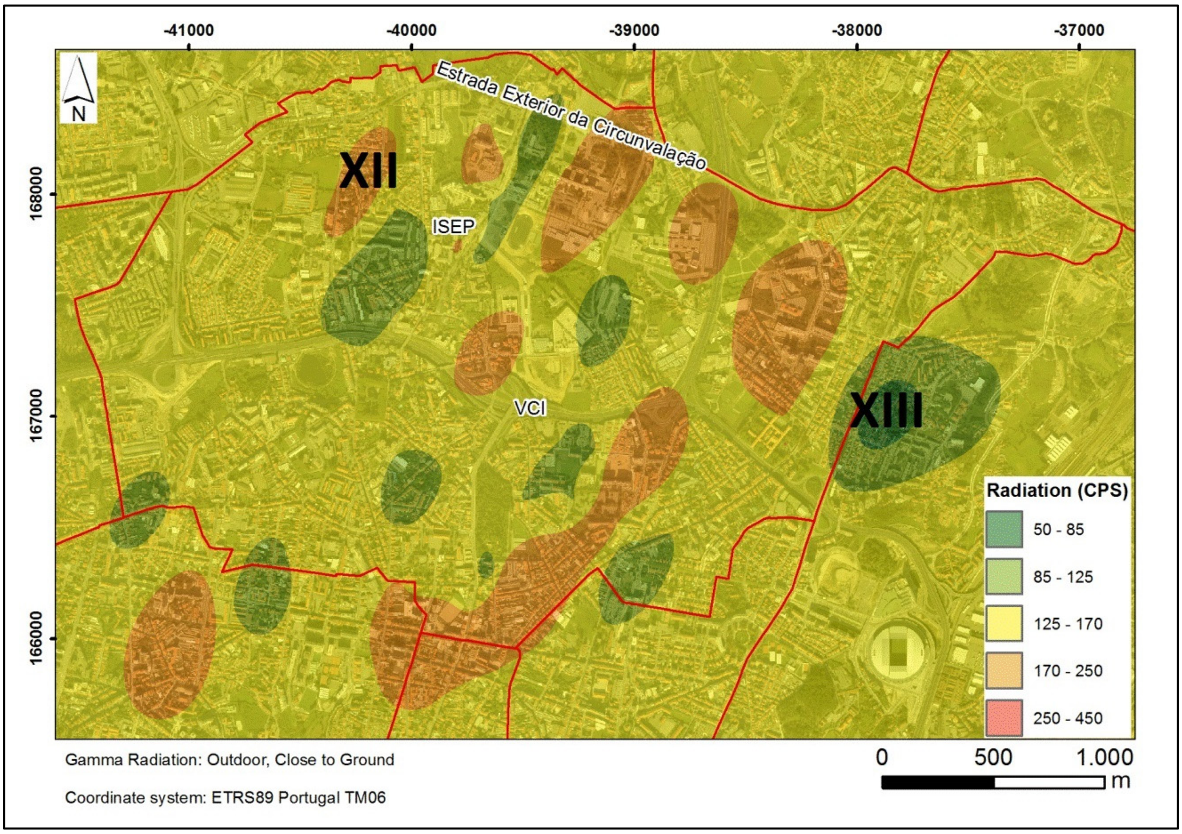


Figure 31. Outdoor: close to ground total gamma radiation measurements.

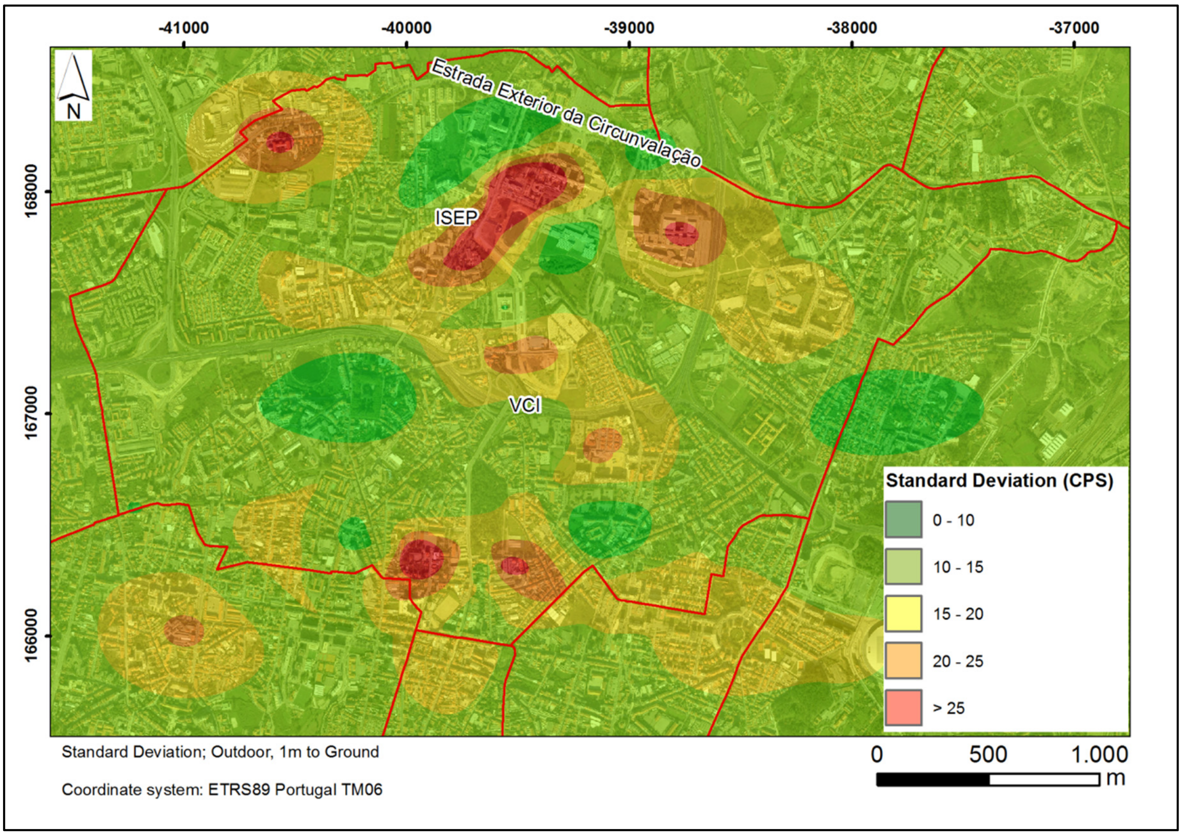


Figure 32. Outdoor: 1m to ground standard deviation spatial distribution.

The spatial distribution of the standard deviation was also analysed in the direct measurements but only for maps representing the measurements at 1m to ground. Not all the red areas from Figure 32 are coincident with the red areas from Figure 30 but the majority is.

Case study C

Values presented on Figure 33 values vary from **50** to **450** cps. The location identified with XIV represents the maximum that was measured in the tunnels of Porto. Despite these high values, this is not a concern because the tunnels do not have public access. They can only be visited by authorized identities. The minimum, (XV) was measured at Ávilas Park.

In Figure 34 values vary between **40** and **750** cps. Despite the variation of the values (minimum and maximum ones), they are coincident with those represented in Figure 33. It is important to say that this kind of measurements has only 21 and 22 values, respectively. As it was mentioned before, the magnitude of the obtained values may be due to the present of evansite (uranium mineral). The total gamma radiation level is higher at 1m to ground, as can be seen in Figure 33; the red area is higher than the one in Figure 34 prove that evansite is much more present in the walls of the tunnels than at the soil level.

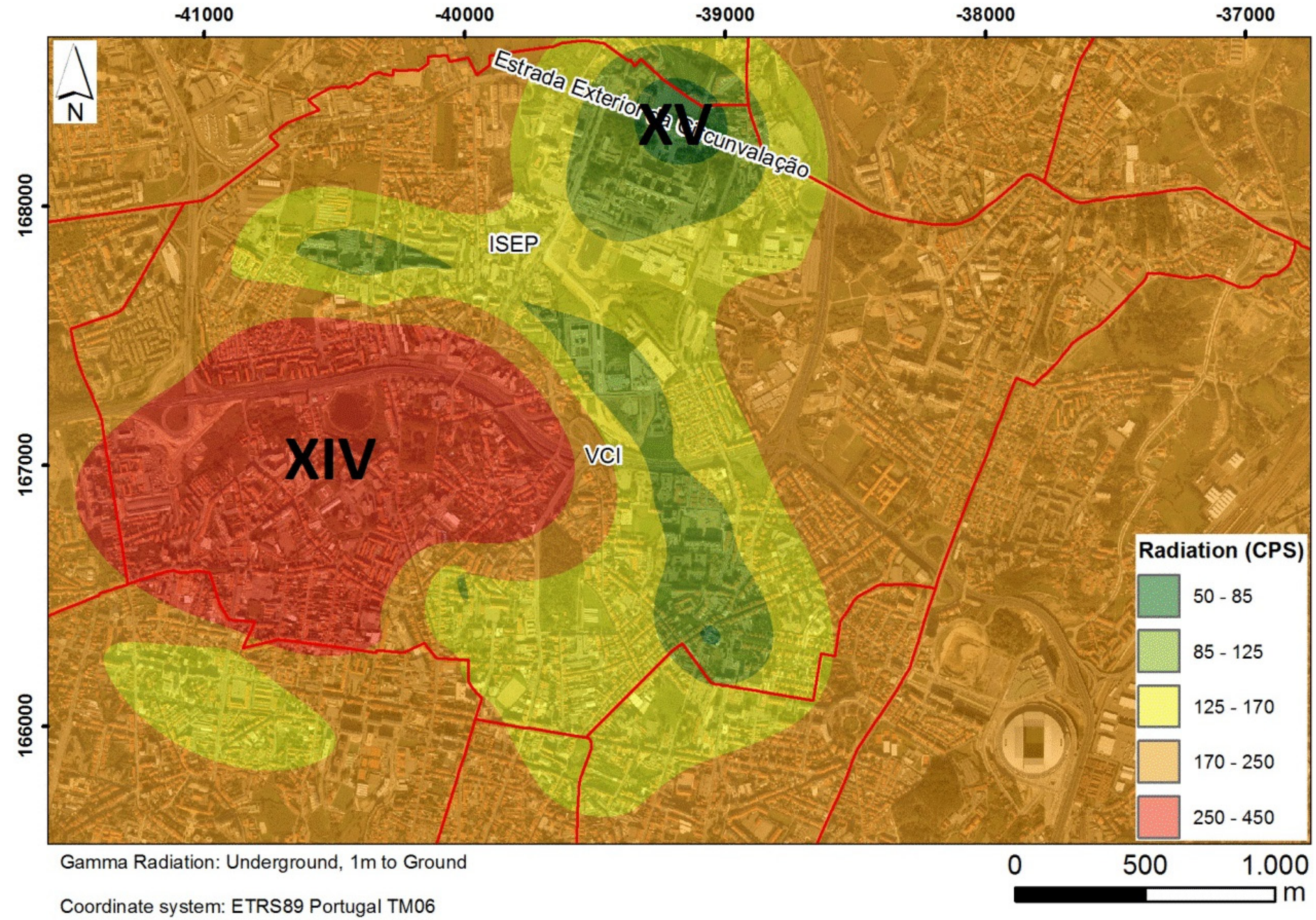


Figure 33. Underground: 1m to ground total gamma radiation measurements.

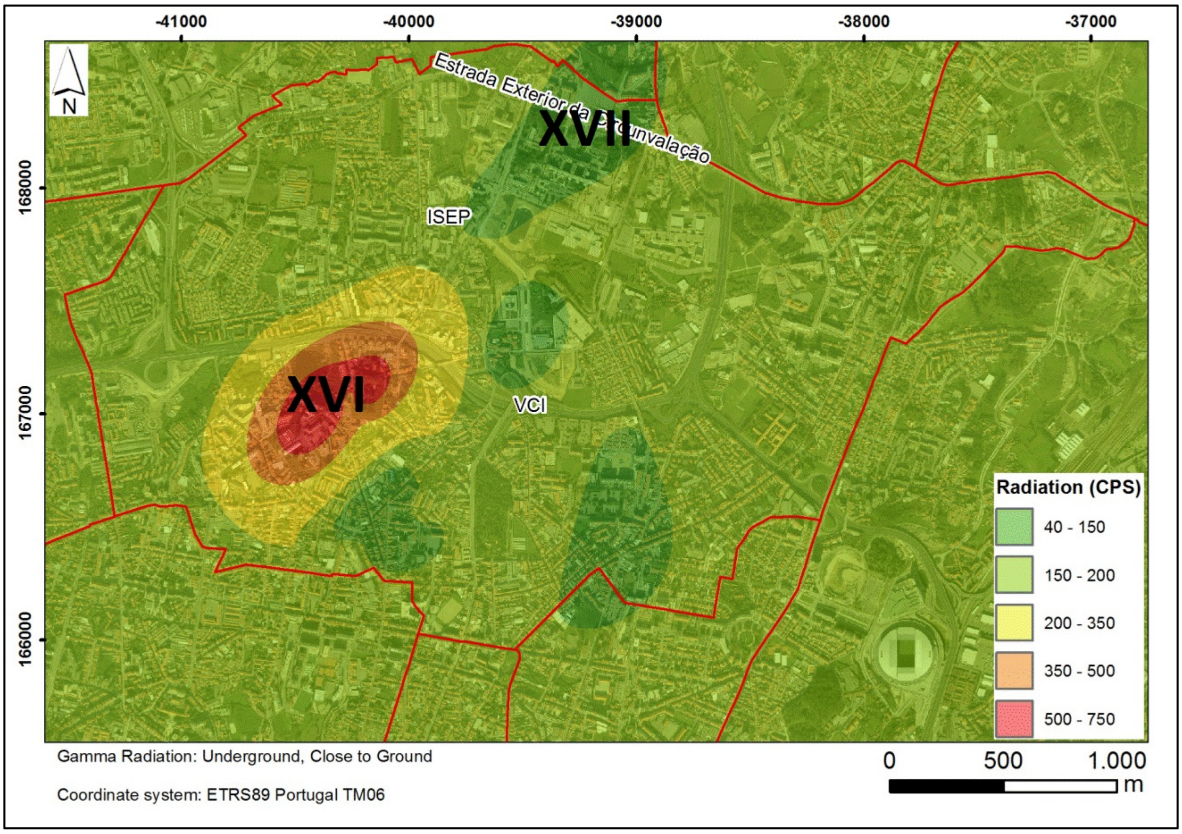


Figure 34. Underground: close to ground total gamma radiation measurements.

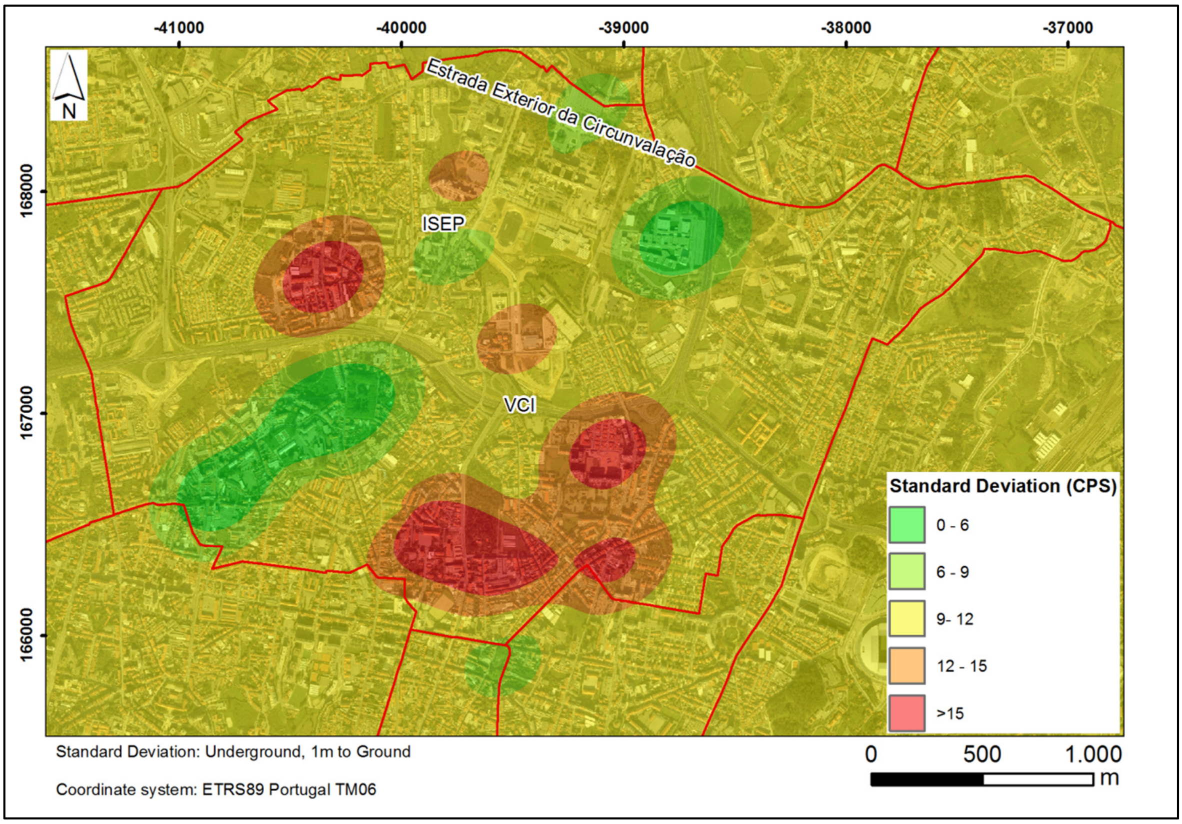


Figure 35. Underground: 1m to ground standard deviation spatial distribution.

The standard deviations of the spatial distribution of the direct measurements were also analysed, but only for maps representing the values at 1m to ground.

4.2 Spatial distribution of data collected related with humidity, temperature and atmospheric pressure

Data of humidity, temperature and atmospheric pressure was added alongside with direct and indirect radiation measurements and represented in outdoor maps. This data was acquired from Pedras Rubras meteorological station and is represented in Figure 36, Figure 37 and Figure 38.

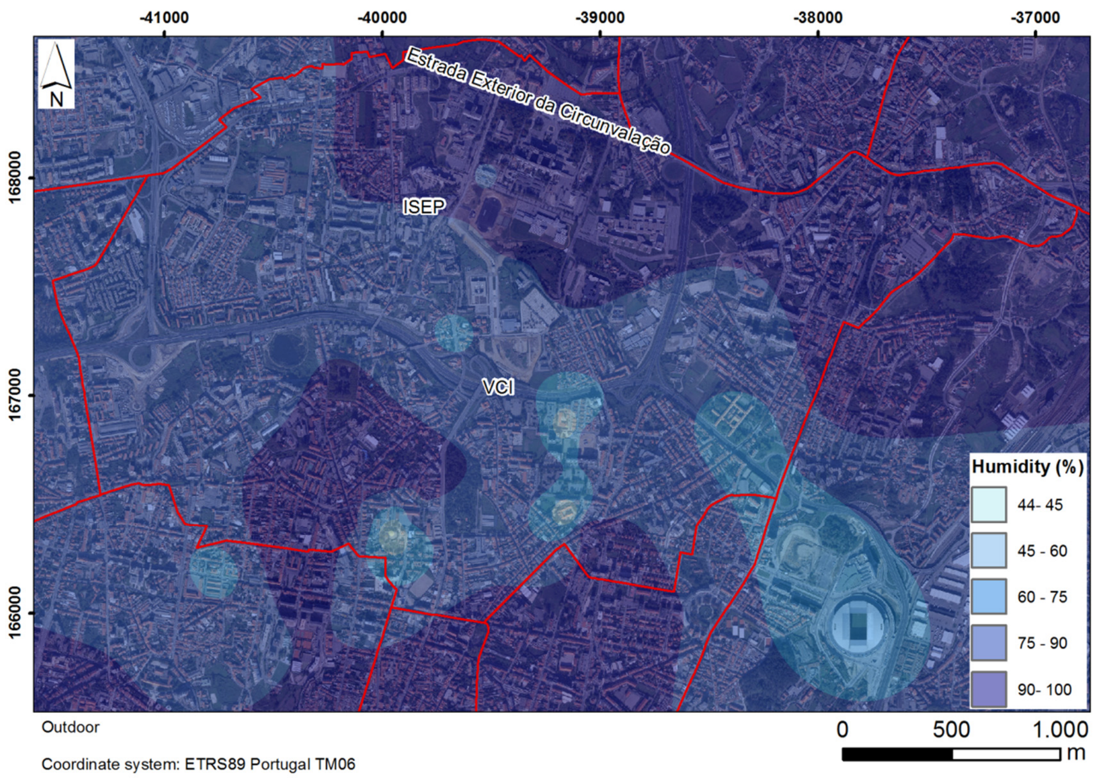


Figure 36. Geographic representation of humidity.

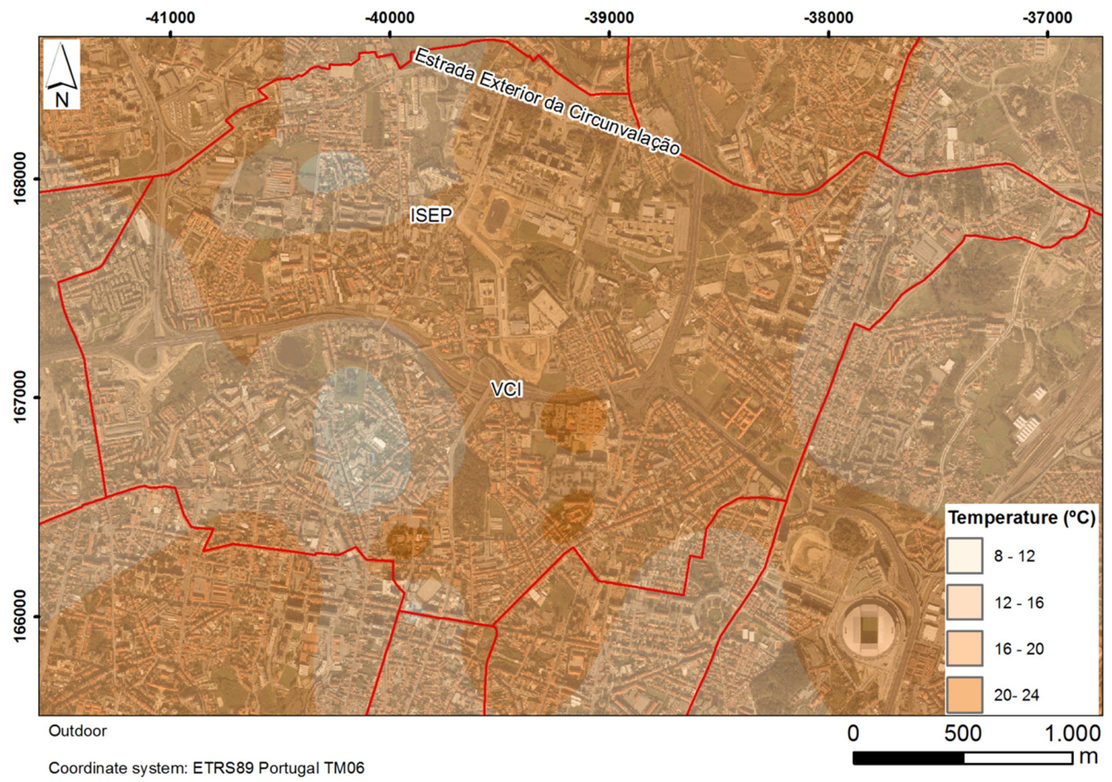


Figure 37. Geographic representation of temperature.

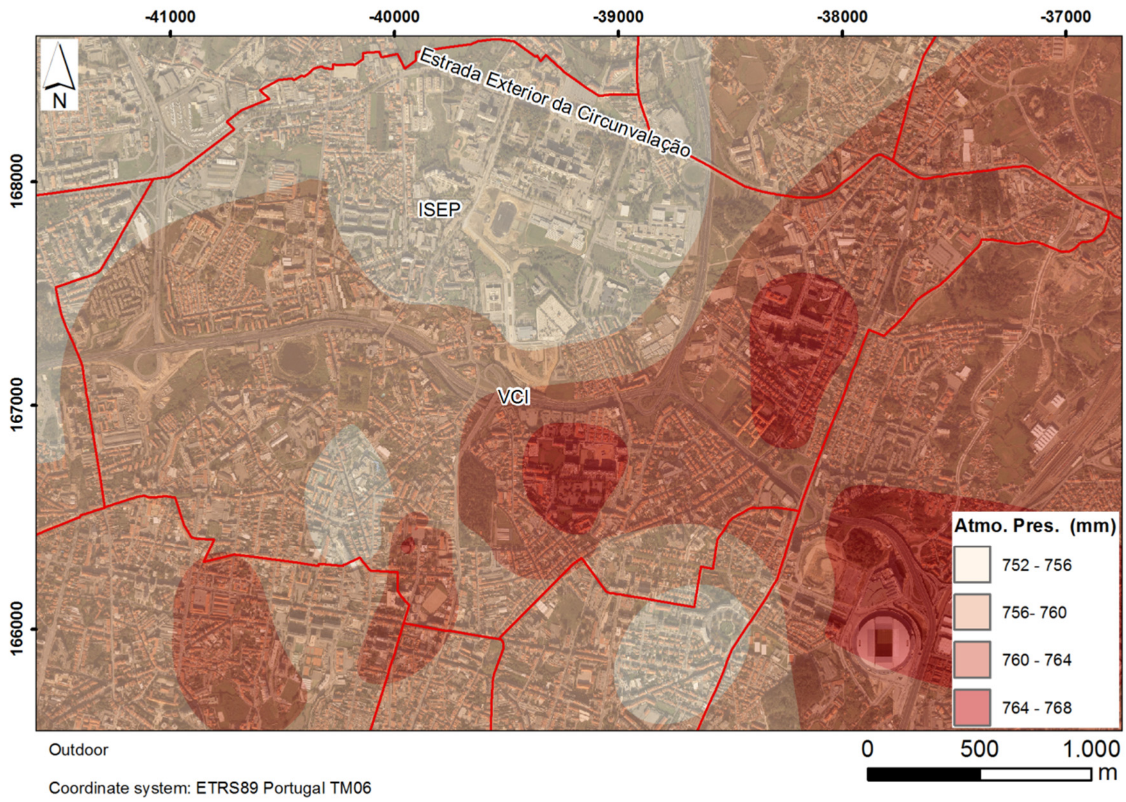


Figure 38. Geographic representation of atmospheric pressure.

4.3 Outdoor total gamma radiation measurements and meteorological parameters analysis

Relation Analysis allowed to understand if exists some kind of connection between gamma radiation content and Humidity, Temperature and Atmospheric Pressure. In this way, we tried to understand if the variation of these three parameters had some kind of influence on the total gamma radiation level; or if effectively does not exist any relation between all the data collected of meteorological parameters and the direct and indirect total gamma radiation. This was only made for outdoor measurements. The hourly values for the humidity (Figure 39 and Figure 40), temperature (Figure 41 and Figure 42) and atmospheric pressure (Figure 43 and Figure 44) were considered for the same time of each outdoor measurement. Therefore, the overlays were made with outdoor total gamma radiation.

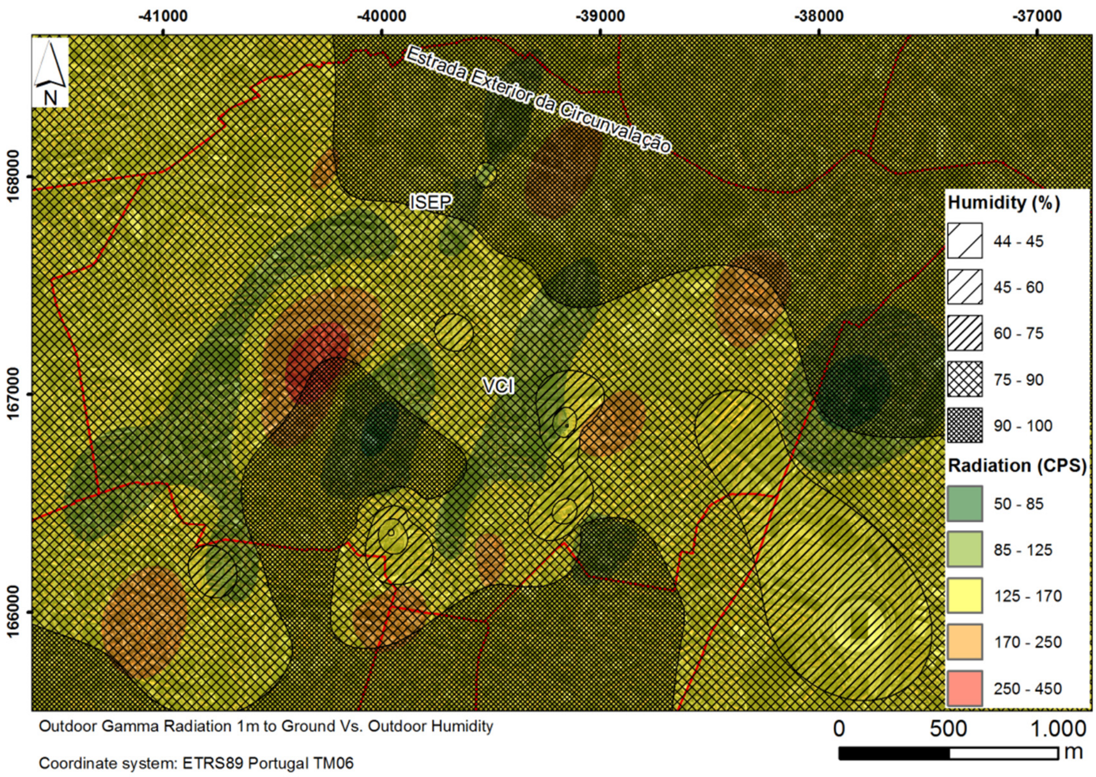


Figure 39. Outdoor total gamma radiation vs. humidity.

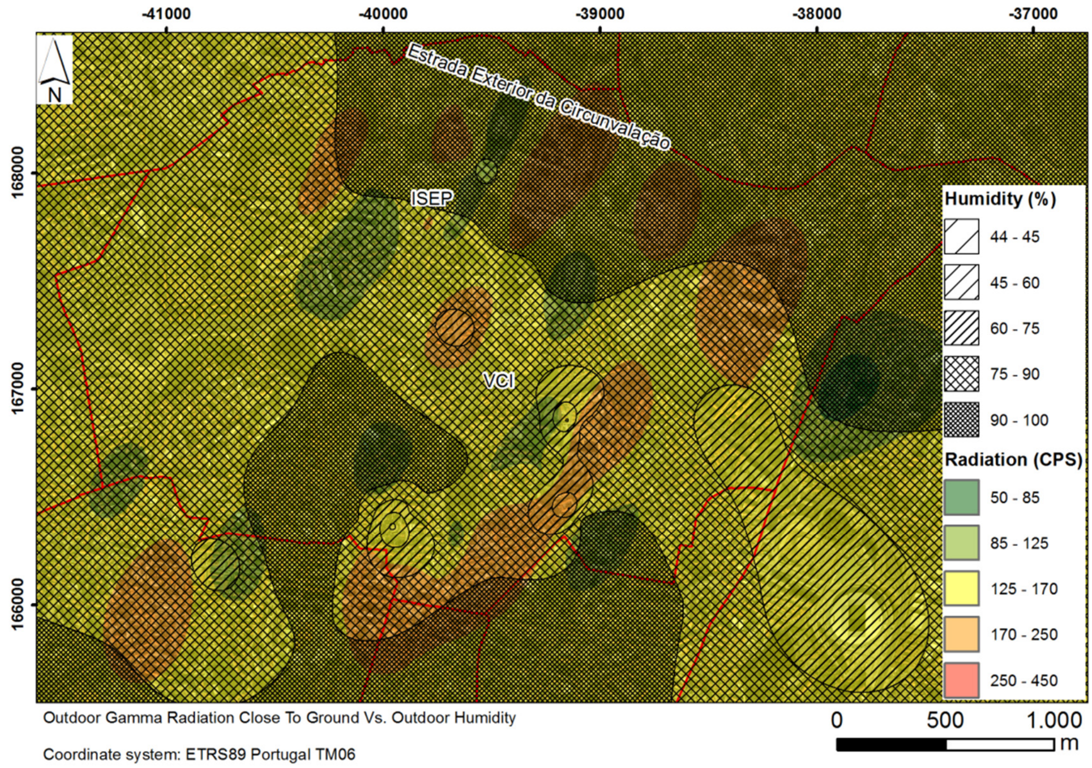


Figure 40. Outdoor total gamma radiation vs. humidity.

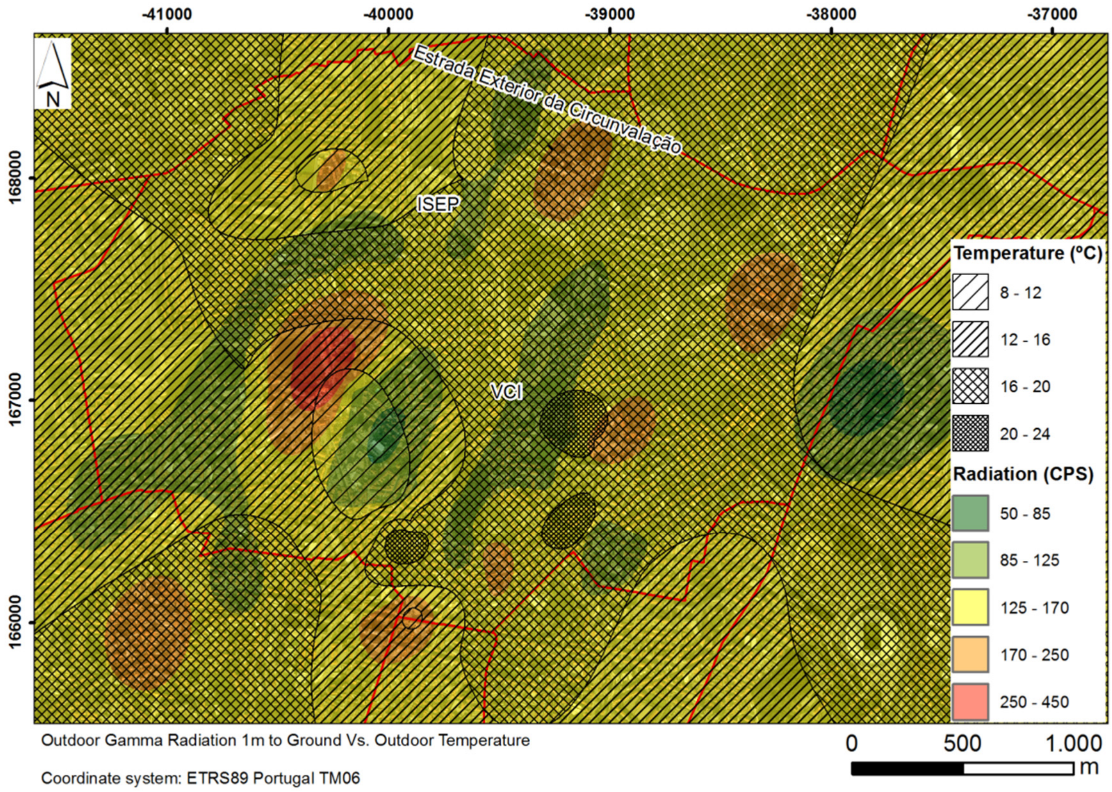


Figure 41. Outdoor total gamma radiation vs. temperature.

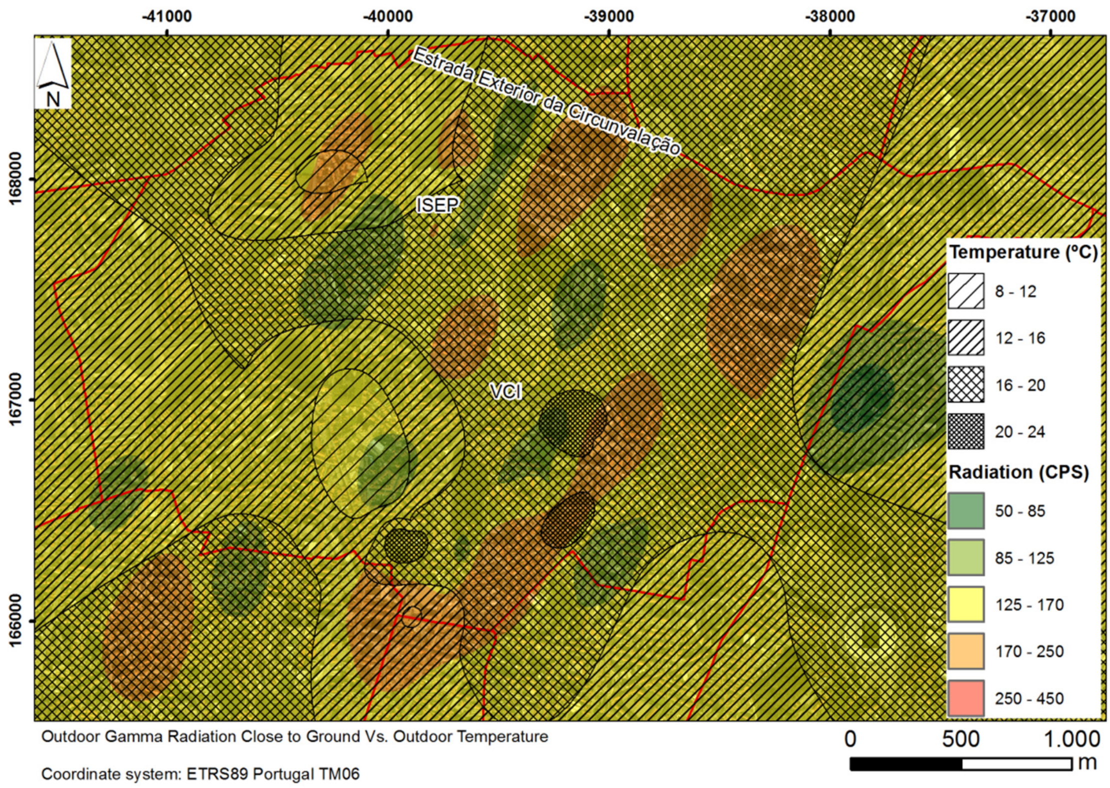


Figure 42. Outdoor total gamma radiation vs. temperature.

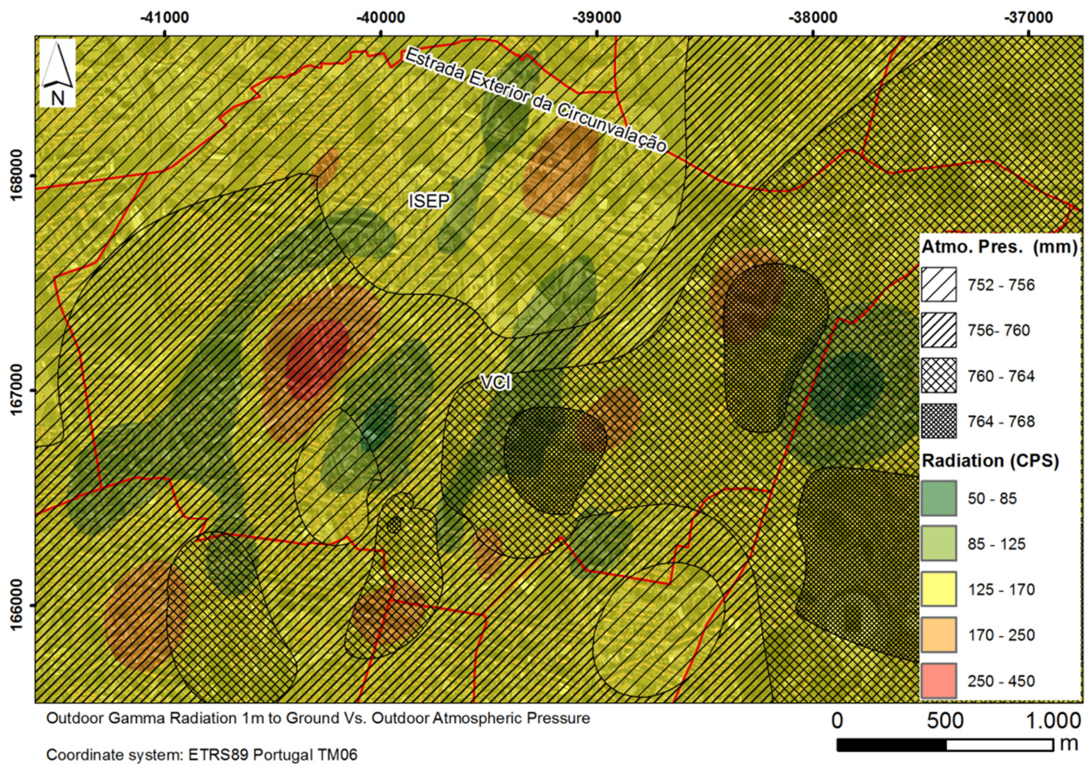


Figure 43. Outdoor total gamma radiation vs. atmospheric pressure.

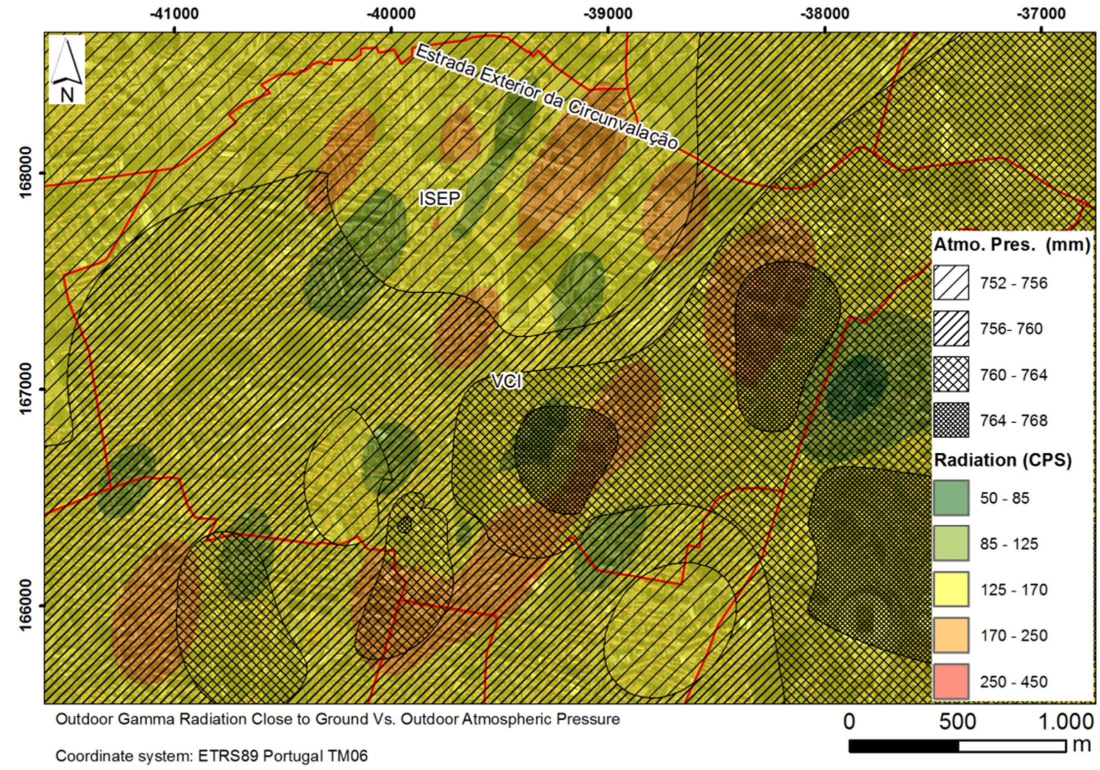


Figure 44. Outdoor total gamma radiation vs. atmospheric pressure.

None of the elaborated overlays shows any kind of connection between radiation and the meteorological variable overlaid. It is necessary to have caution; it would be better if were taken values in a longer period, making the analysis more consistent. However, the analysis carried out can be considered as valid.

4.4 Data analysis: indirect radiation measures

The analysis of indirect radiation measures was divided in two study cases: study case D (surface) and study case E (underground) represented in Table 8. The division of data, as cases of study, was made concerning the location of the measurement: surface or underground. For the study case D two analysis were considered as the maximum from gamma radiation dose rate (1): **23,46** µSv/h is very high when compared with the other values collected; probably this is due to an overflow of the equipment. Therefore, the analysis gamma radiation dose rate (2) was made without this value. All the comparisons between cases of study were made based on gamma radiation dose rate (2).

The organized data is included in Appendix 7.

Table 8. Data analysis gamma and total radiation doses.

Information		Mean (μSv/h)	Median (μSv/h)	Std. (μSv/h)	Min. (μSv/h)	Max. (μSv/h)	N
Case study D-Surface	Gamma Radiation Dose Rate(1)	0,69	0,30	2,84	0,13	23,46	69
	Gamma Radiation Dose Rate(2)	0,36	0,25	0,60	0,13	4,97	68
	Total Radiation Dose Rate	0,33	0,26	0,33	0,12	2,47	69
Case study E-Underground	Gamma Radiation Dose Rate	0,89	0,49	0,80	0,18	2,23	14
	Total Radiation Dose Rate	1,31	0,92	1,22	0,19	4,01	14

From gamma radiation dose rate study analysis, case study E is the one that presents the highest mean: **0,89** μSv/h. case study E also presents the highest mean of Total Radiation Dose Rate: **1,31** μSv/h. The lowest mean of gamma radiation dose rate belongs to Case study D (gamma radiation dose rate (2)): **0,33** μSv/h.

Analysing minimum values: case study D has both minimums **0,13** and **0,12** μSv/h, from gamma radiation dose rate (2) and total radiation dose rate (respectively). The highest maximum belongs to case study D, gamma radiation dose rate (2): **4,97** μSv/h, being the maximum of Total Radiation Dose Rate from case study E: **4,01** μSv/h.

It is necessary to have in mind that the number of data that allowed case study E is 14 measurements. Therefore, this represents only a preliminary approach. More studies should be carried out in the future.

4.4.1 Spatial analysis of total and gamma radiation dose rates

The spatial analysis of total and gamma radiation dose rates was elaborated respecting the same aspects as the previous spatial analysis for data collected with Scintillometer SPP2.

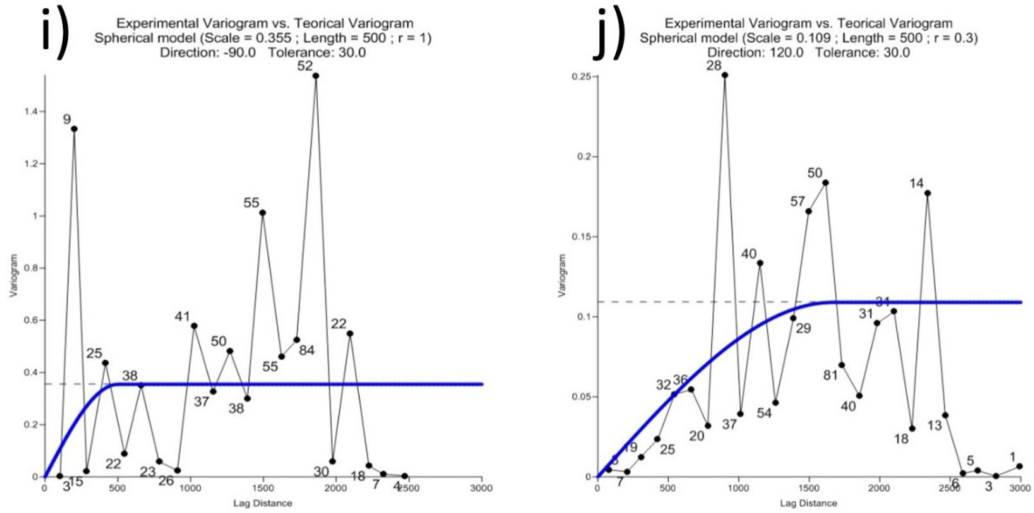


Figure 45. Case study D – i) surface: gamma radiation dose rate, j) surface: total radiation dose rate.

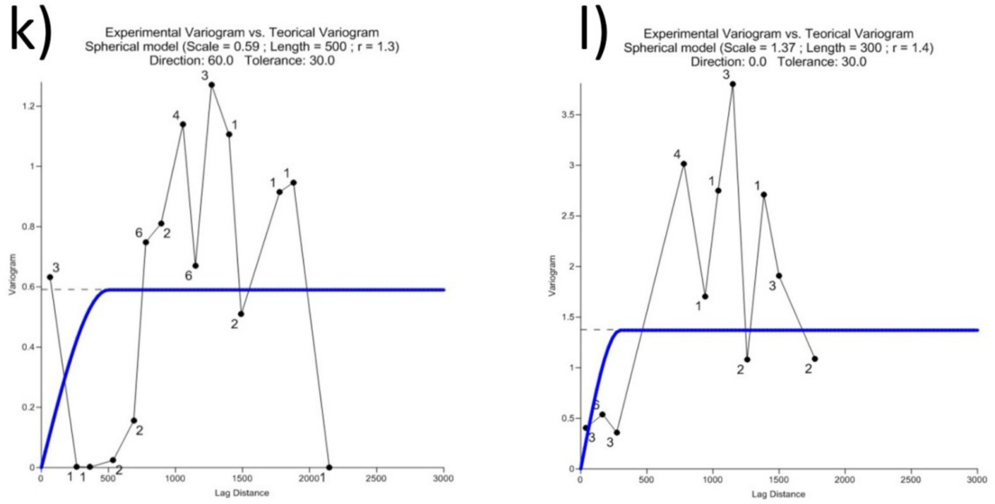


Figure 46. Case study E – k) underground: gamma radiation dose rate, l) surface: total radiation dose rate.

Case study D is the one that better fits into the chosen model. As for case study E, the number of collected values is not meaningful, the distribution does not fit to the model and it would not fit to any other model because the number of values is not representative as mentioned before. The study of Total Radiation Dose Rate should be further explored at Paranhos sector.

4.4.2 Geographic analysis of the collected data from gamma and total radiation doses

Based on the fitted theoretical variogram, several maps were obtained to represent the gamma radiation dispersion. The maps relative to each case of study and the own descriptive analysis are presented in the following figures.

Case study D

On case study D the distribution of gamma radiation dose rate (2) varies between **0** and **>0,4** µSv/h (Figure 47). The minimum, **0,13** µSv/h, was measured at IPO (XIX); the maximum value represented by (XVIII*), was measured at Centro Regional do Sangue do Porto; (XVIII) represents the previous maximum that was considered an overflow and it was measured in a Private Building of Serpa Pinto Street.

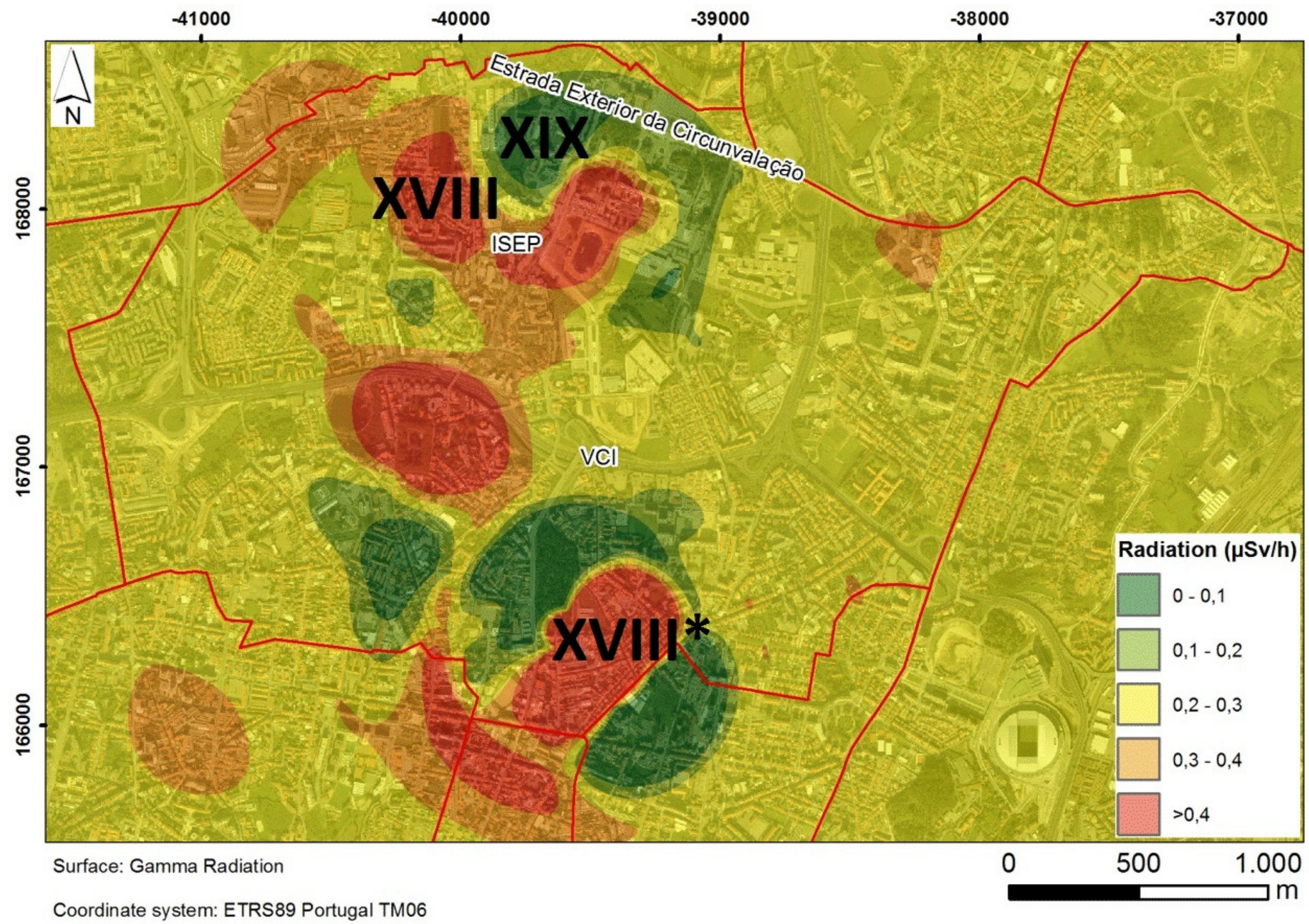


Figure 47. Geographic representation of gamma radiation dose measurements: surface.

Antiquate construction with old materials could be one of the reasons to explain why there are some areas with higher values when compared with the values collected in others areas. Being granite the most representative rock in Porto's geology, the values have tendency to become higher as it is a potential radiation emitter.

On Figure 48 the distribution of values varies between **0** and **>0,4** µSv/h. The minimum is coincident with the area from the one measured on Figure 47 (XX). However, the location where the maximum value was registration formed (**2,47** µSv/h) is not coincident with the previous one (XXI).

Both figures have minimums with coincident areas, XIX and XX; however, the maximum were not measured at the same place XVIII* and XXI.

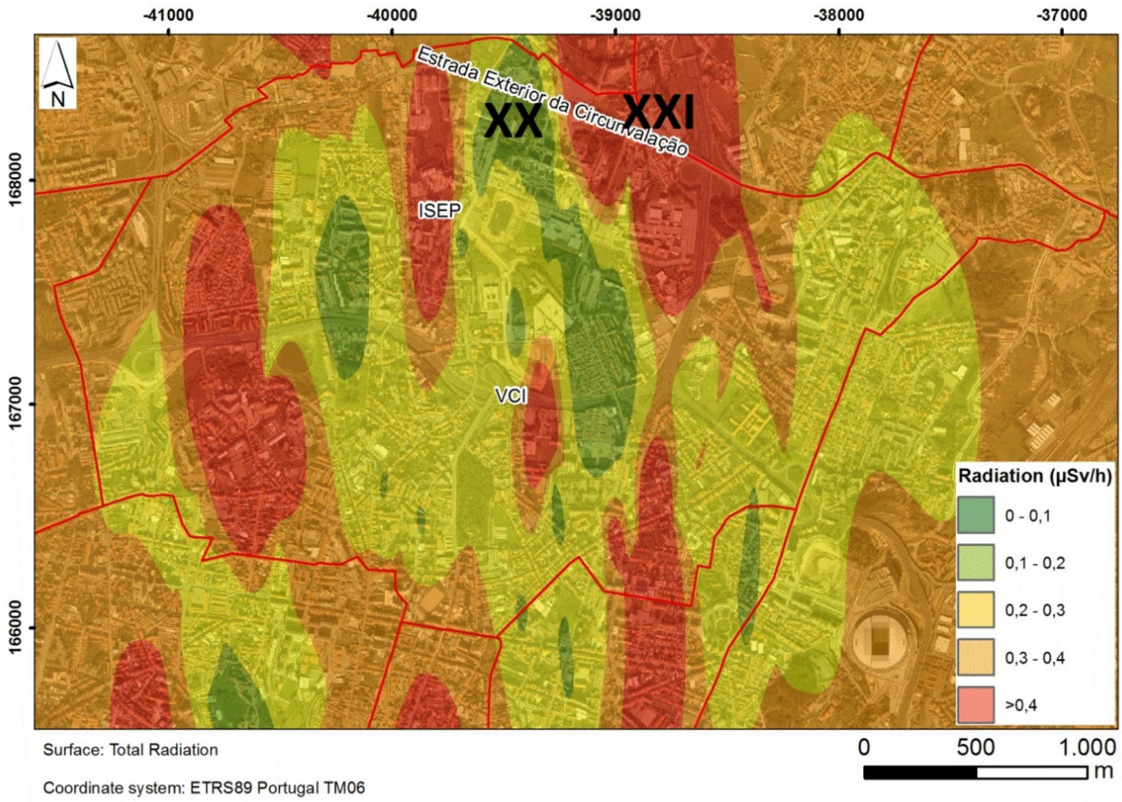


Figure 48. Geographic representation of total radiation dose measurements: surface.

Case study E

On Figure 49 the distribution of values varies from **0** to **>0,4** µSv/h. The minimum (XXII) **0,18** µSv/h was registration formed at Subway Station Combatentes and the maximum at Mananciais do Porto: **2,23**µSv/h.

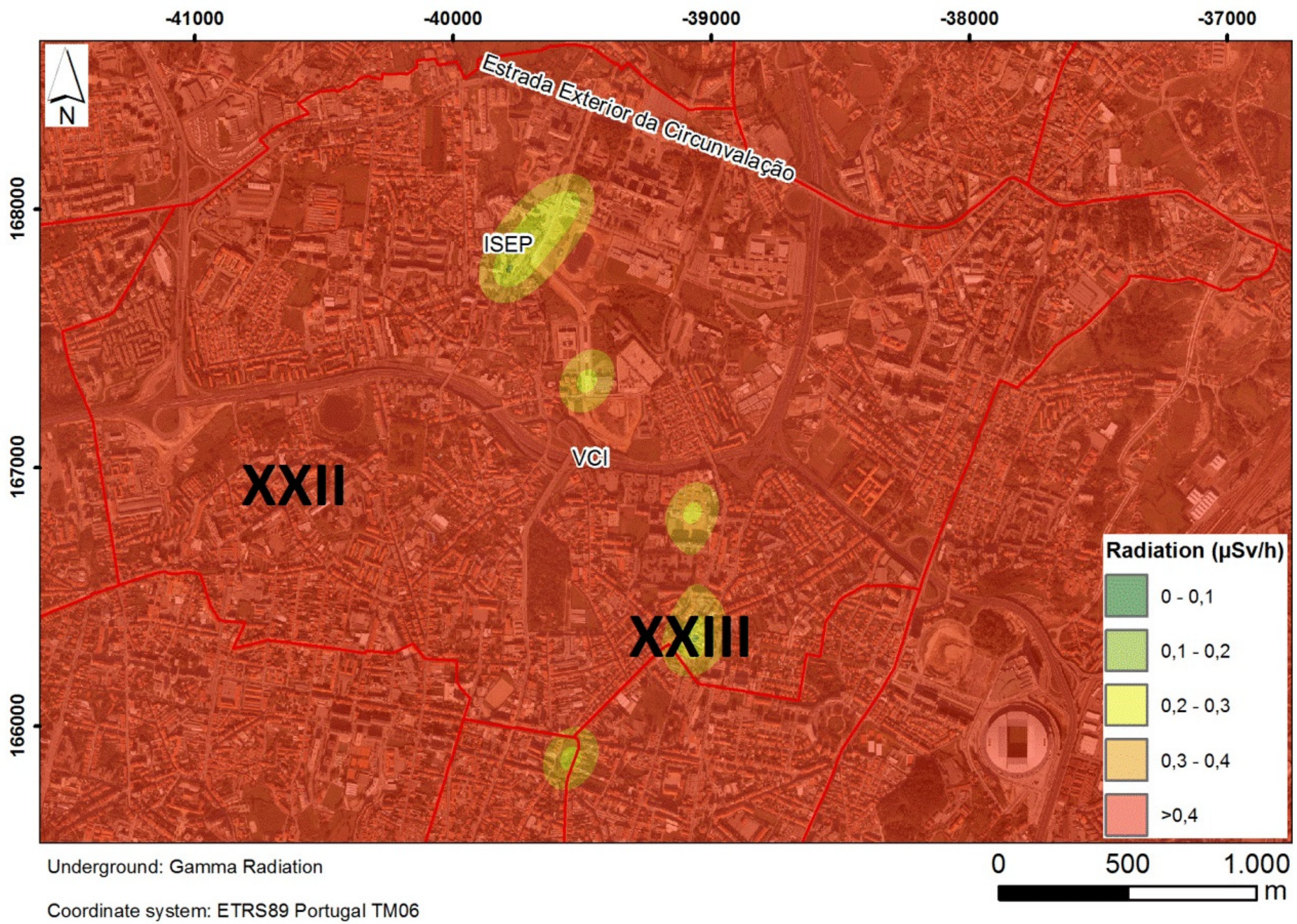


Figure 49. Geographic representation of gamma radiation dose measurements: underground.

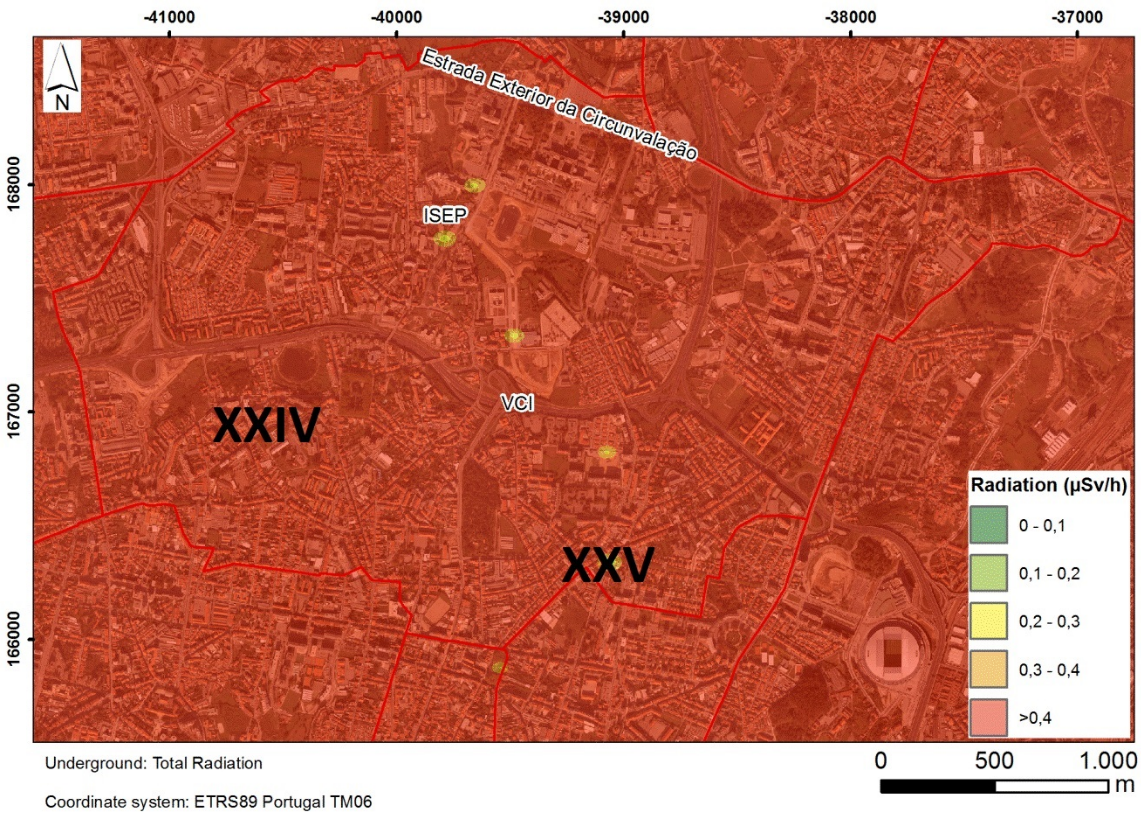


Figure 50. Geographic representation of total radiation dose measurements: underground.

On Figure 50 the distribution varies between **0** and **>0,4** µSv/h. Both minimum and maximum are in coincident areas with the same areas from Figure 49. Both maximums were measured at Mananciais do Porto.

We should have caution as Figure 49 and Figure 50 represent only 14 collected measurements. In the future, it would be advisable to carry out more dose rates studies exploring all the underground structures of Paranhos.

4.5 Outdoor total and gamma radiation doses and meteorological parameters analysis

Relation Analysis allowed to understand if there is a relation between total and gamma radiation dose rate content and metrological parameters such as Humidity, Temperature and Atmospheric Pressure. We tried to understand if the variation of these three parameters had some kind of influence on the surface total and gamma radiation dose rate level, or not. This analysis was made only for the surface measurements. Meteorological data was collected from meteorological station of Pedras Rubras. Data for humidity (Figure 51 and Figure 52), temperature (Figure 53 and Figure 54) referring to the time of measurement that was selected for this analysis. Atmospheric Pressure was not considered because its variation was not GISnificant. Therefore, the overlays were made with surface data.

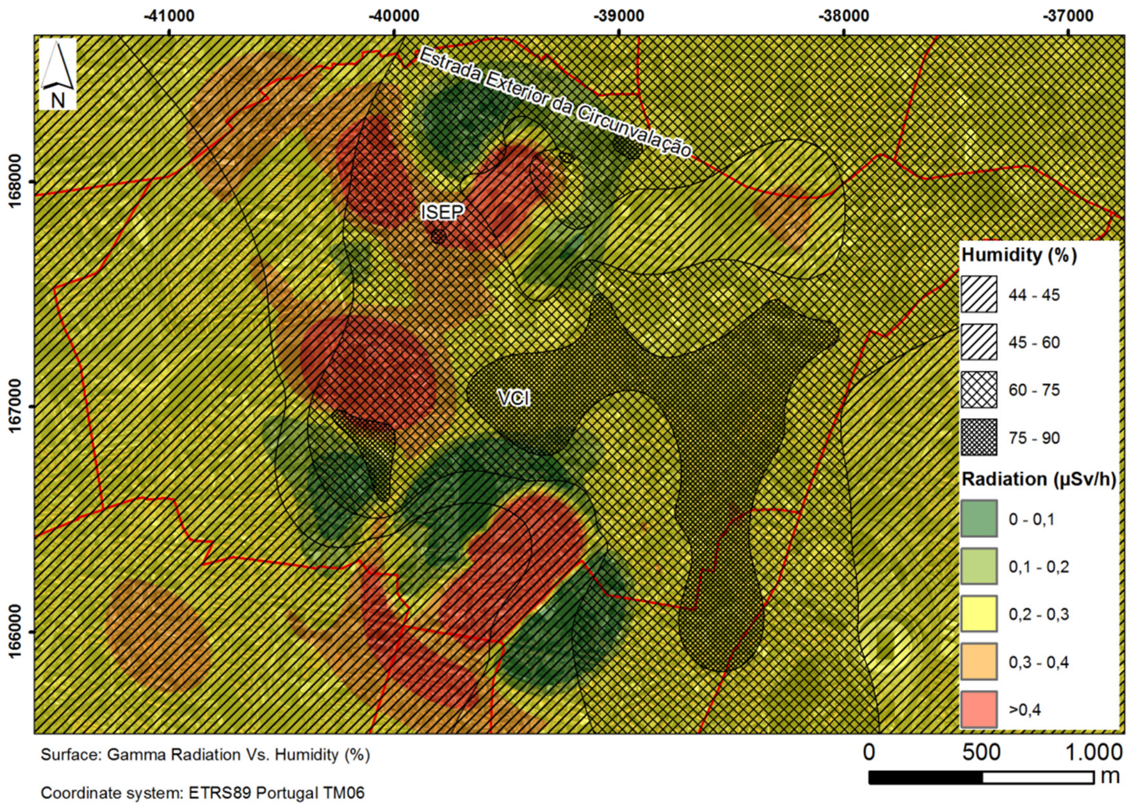


Figure 51. Geographic representation of gamma radiation doses measurements: surface vs. humidity.

As seen before with gamma radiation maps it was not possible to observe any relation between total and gamma radiation doses and the selected meteorological data. This could be explained by the fact that it would be necessary to spend more time measuring general data, several times in a year to be representative of any potential relation.

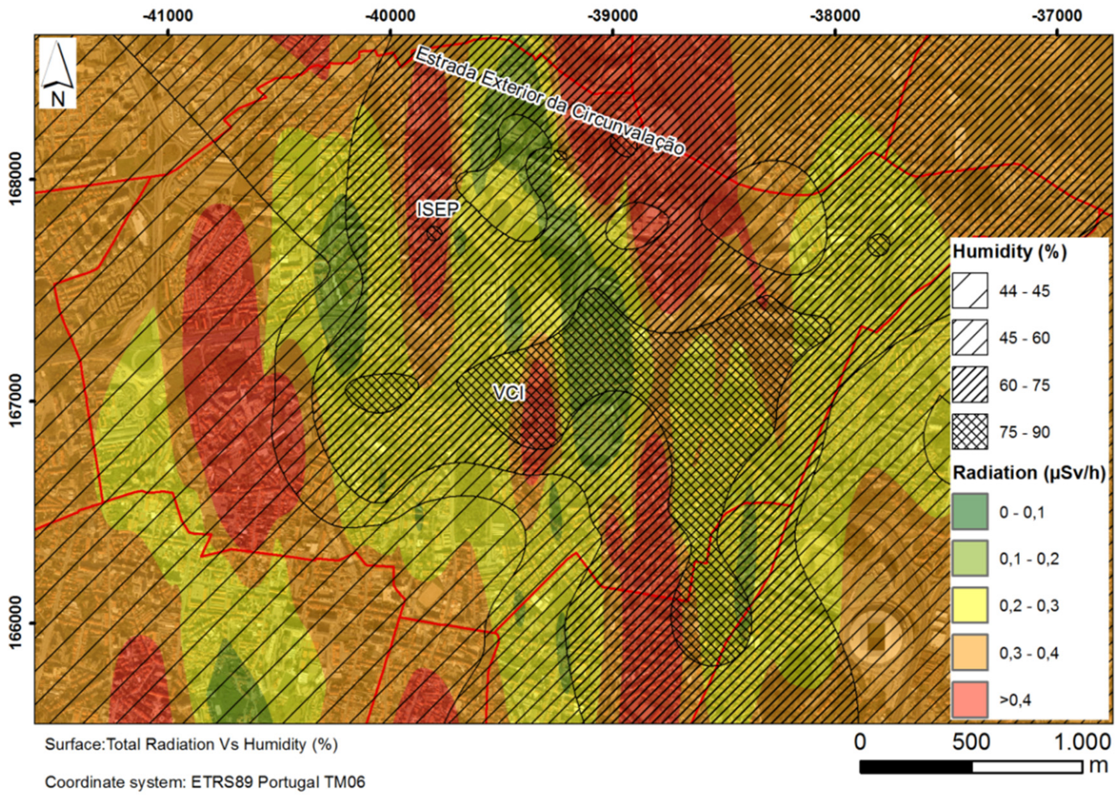


Figure 52. Geographic representation of total radiation doses measurements: surface vs. humidity.

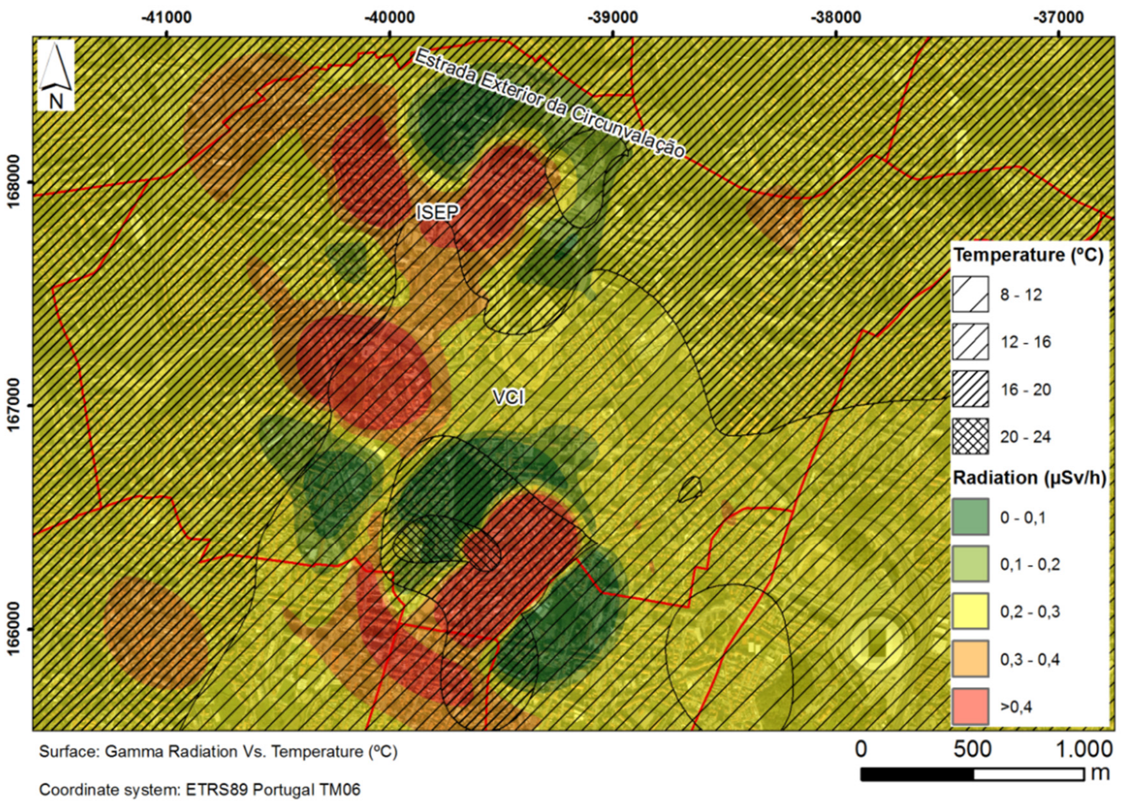


Figure 53. Geographic representation of Gamma Radiation Doses measurements: Surface vs. Outdoor Temperature.

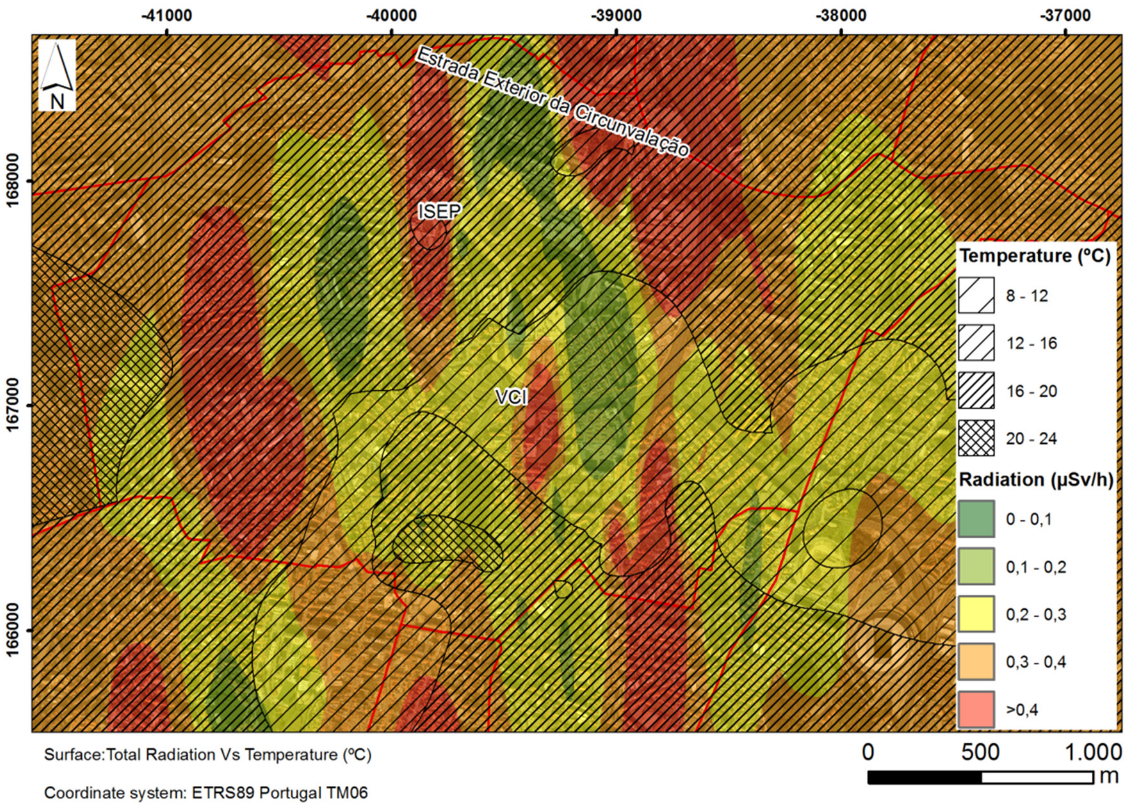


Figure 54. Geographic representation of Total Radiation Doses measurements: Surface vs. Outdoor Temperature.

4.6 Dose rate calculation through radiation values

Both equipments used in this study measured radiation in different ways, expressing results in different units. The first purpose in using GAMMA SCOUT® was to measure radiation dose rates (µSv/h). However GS-3 also measures total gamma radiation in counts per second (cps).

Doses rates cannot be directly compared with gamma radiation values. However, a relation between radiation (cps) and dose (µSv/h), for this study, may be established. In addition, as both equipments measure gamma radiation, it was possible to establish a comparison term.

This analysis considered with 81 values of gamma radiation measurements from 72 different sample sites.

The following histograms were used to analyse the distribution of values, measured directly with both equipments.

From Figure 55 and Figure 56 it is possible to observe that there is a concentration peak for the results obtained with both equipments. Scintillometer SPP2 NF has a concentration of values at 150 cps, and for GAMMA SCOUT® the concentration peak occurs at 1,2 cps. Both distributions seem to adjust into a lognormal distribution. This should be sustained with further measurements comparing the results at different intervals. However, the few differences observed for others ranges may be explained by the way the results are given: Scintillometer SPP2 NF has an analogical output (a needle that needs to be stabilized to allow the readings) and GAMMA SCOUT® has a digital output giving an exact value (more accuracy reading).

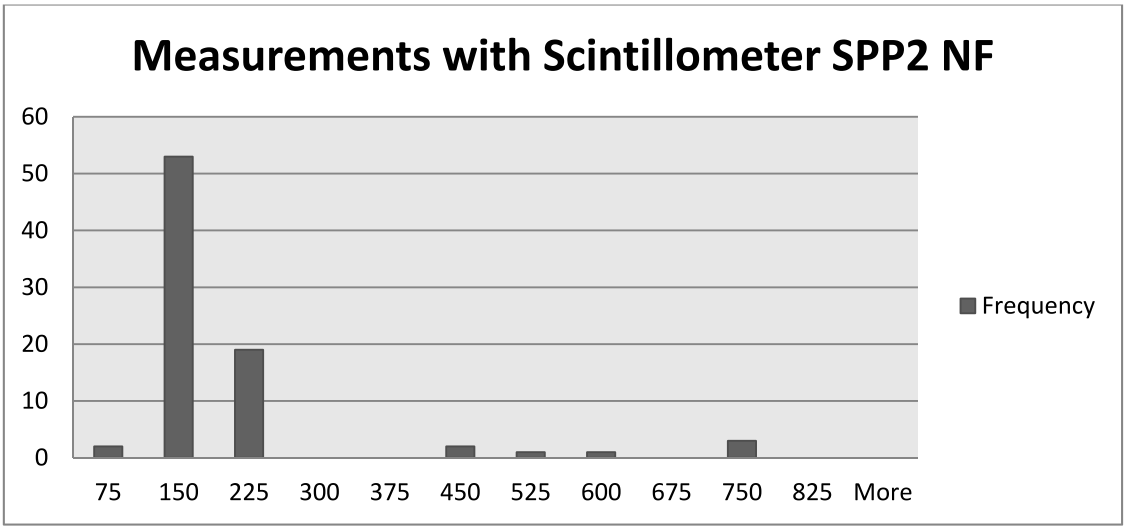


Figure 55. Histogram representing total gamma radiation variability (Scintillometer SPP2 NF).

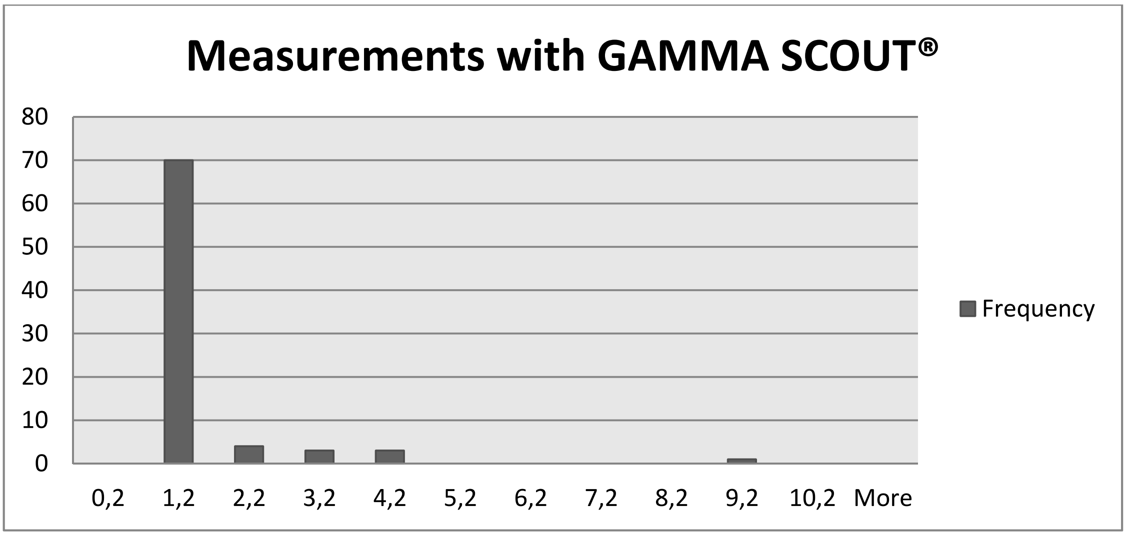


Figure 56. Histogram representing gamma radiation variability (GAMMA SCOUT®).

A general analysis of some statistical parameters such as mean, median, standard deviation, minimum, maximum, gap and N (Table 9) was performed for the relation values established between Scintillometer SPP2 NF radiation measurements and GAMMA SCOUT® dose measurements.

Table 9. General statistical parameters for the relation between SPP2 NF radiation measurements and GAMMA SCOUT® dose measurements.

Relation analysis	Mean (cps/µSv/h)	Median (cps/µSv/h)	Std. (cps/µSv/h)	Min. (cps/µSv/h)	Max. (cps/µSv/h)	Gap (cps/µSv/h)	N
Scintillometre SPP2 / GAMMA SCOUT®	524,01	537,25	192,08	37,61	1287,88	1250,27	81,00

This comparison was not made with radiation and dose values from GAMMA SCOUT® because its variability is insignificant. The relation values doesn't present a great discrepancy, being the minimum 1,76 cps/µSv/h and the maximum 1,78 cps/µSv/h. Therefore, we can establish a relation between radiation and doses for this equipment too (Table 10):

Table 10. Relation: radiation/doses from GAMMA SCOUT® collected data.

GAMMA SCOUT®: Radiation/Doses	
µSv/h	**Cps**
1,00	1,77

Higher values are assumed at the relation ones between Scintillometre SPP2 NF and GAMMA SCOUT®. It also proves the inGISnificant variability that occurs with GAMMA SCOUT®.

Attending that the limit range established by the UNSCEAR varies between 1,00 and 10,00 mSV/y we can affirm that the value represented by GAMMA SCOUT® is acceptable: 8,76 mSV/y.

We have also established a comparison between the relation values obtained for GAMMA SCOUT® (radiation and doses): 1,77 cps/µSv/h (Table 11).

Table 11. Radiation/ radiation dose rates relation.

GAMMA SCOUT® obtained value **(cps/µSv/h)**	According to Ken Jorgustin: relation value of Cs137 isotope **(cps/µSv/h)** (Jorgustin, 2011)	According to Michael Van Broekhoven **(cps/µSv/h)** (Broekhoven, 2012)
1,77	0,50	0,33

The values represented are in the same greatness order, being possible to consider this comparison.

4.7 Construction materials analysis

A preliminary approach was made for the analysis of gamma radiation emitters. The purpose was to be aware of which one of the considered types of construction materials would be the potential higher radiation emitter. The prevailing materials (the most representative) from all the sample sites were pointed, attending that construction materials have different chemical components in their composition, which may be potential radiation emitters. In this case, it is expected that some materials emit higher doses than others attending to different factors such as internal constitution, how is being used and it was plied among other facts.

In this way, a statistical analysis was carried out for all the materials: Igneous Rock (mostly granite), Sedimentary Rock, Metamorphic Rock (mostly marble), Brick, Cement, Concrete, Asphalt, Tile, Linoleum, Wood, and Dirt. All data from direct measurements was considered in this analysis.

All the considered materials are presented in Table 12 as well as their code number.

Table 12. List of all materials used in both registration forms.

Type of Material	Code number
Igneous Rock	1
Sedimentary Rock	2
Metamorphic Rock	3
Brick	4
Cement	5
Concrete	6
Asphalt	7
Tiles	8
Linoleum	9
Wood	10
Soil	11

Table 13 was elaborated based on the statistical analysis for each material comparing mean minimum, maximum and frequency of the material (count) referring to the direct measurements.

Table 13. Comparisons between all the materials.

Type of material	Code number	Mean of direct gamma radiation (cps)	Minimum (cps)	Maximum (cps)	Count N
Igneous Rock	1	217	77	900	68
Sedim. Rock	2	112	87	147	18
Metam. Rock	3	115	91	190	22
Brick	4				0
Cement	5	121	44	179	24
Concrete	6	198	97	617	12
Asphalt	7	150	94	238	60
Tiles	8	128	41	190	52
Linoleum	9	121	50	167	38
Wood	10	167	149	190	10
Dirt	11	126	106	141	6

- ❖ Mean of direct gamma radiation (cps): from all 11 materials, Igneous Rock (mostly granite) was the one with the highest value, **217** cps, belonging the lowest value, **112** cps to the Sedimentary Rock Material.
- ❖ Minimum (cps): wood is the material with higher minimum, **149** cps, corresponding to tiles the lower minimum, **41** cps;
- ❖ Maximum (cps): the highest maximum corresponds to igneous rock (mostly granite), **900** cps and it was measured at Mananciais do Porto. The lowest maximum corresponds to dirt: **141** cps;
- ❖ Count (frequency of the material): igneous rock was the one found with more frequency. Among the sampling locations brick was the construction material never found, having zero counts. Therefore, the less counted material after brick was dirt with six counts.

From all types of materials studied, Igneous Rock was the most representative and the one with the highest value (**900** cps). The highest maximum measured on this type of material can be explained by the presence of Evansite in the tunnels underneath Porto city. Evansite is a uranium mineral commonly present in tunnels (Afonso, et al., 2007). Beside evansite it was to expect that igneous rock, particularly granite presented higher values of gamma radiation once it is very common to find in its constitution uranium minerals.

In the future, it would be interesting to do a sampling from all Paranhos construction materials with the purpose of checking if there is some connection between the kind of construction material and gamma radiation content.

Conclusions

5 Conclusions

5.1 Case study A

Case study A is divided in two subcases: A1 and A2. The first one includes all values collected on direct measures and the second one does not include the values measured at the Mining Engineering Department of Faculdade de Engenharia da Universidade do Porto, which, as explained before, is anomalous.

The spatial analysis of data was made using the geostatistical software package named Surfer 8. All four variograms generated (Figure 21) were fitted to the spherical model.

Subcase study A1, measures indoor: at 1m to ground and close to ground with Faculdade de Engenharia da Universidade do Porto. The values obtained are very similar with those from subcase study A2, which also measures indoor: at 1m to ground and close to ground however without Faculdade de Engenharia da Universidade do Porto. Minimums have different interpolated values and coincident areas: **20** and **30** cps at subcase A1 and A2: 1m to ground and close to ground respectively. Although these two cases do not present the same values, both maximums are in the same greatness order, A1 maximums: **620** and **520** cps, indoor: 1m to ground and close to ground respectively and A2 maximums: **190** and **195** cps, indoor: 1m to ground and close to ground respectively.

The maximum of subcase A1 could be considered a hotspot if its origin was unknown. However, as it is known and understood that it does not present a hazard to the public health it was decided to proceed with the subcase study A2.

The maps generated with A2 geoestatistical values (Figure 27 and Figure 28) present some different aspects from previous ones (Figure 24 and Figure 25). This allows us to conclude that the inserted values measured at Faculdade de Engenharia da Universidade do Porto have influence in the creation of the statistics charts, which will be used to generate the maps.

Both subcases maps referring to the measurements close to the ground (Figure 25 and Figure 28) present higher total gamma radiation values than maps with measurements at 1m to the ground (Figure 24 and Figure 27). As Paranhos soil is mostly constituted by granite, which is a potential radiation emitter, this result was expectable.

5.2 Case study B

Case study B is relative to direct outdoor total gamma radiation measures.

The two variograms (Figure 22) generated were adjusted to the spherical model.

The map that represents the measurements at 1m to ground outdoor (Figure 30) and the one that represents the measurements close to ground outdoor (Figure 31) are very similar. Minimum values (XI and XIII) have an equal value (**50** cps), and were measured at the same place, in a farm in front of Colégio do Amial. However, the maximum ones do not coincide in area or in value: **450** cps 1m to ground and **450** cps close to ground. The first one was measured at the entrance of Mananciais do Porto and the second one at Colégio do Amial. The construction materials, the age of the buildings and the architectonic style (old or recent buildings, presence of tunnels under the buildings, with natural ventilation or not) could explain the two maximums obtained.

Higher level of total gamma radiation was found close to ground (Figure 31). As Paranhos soil is almost all constituted by granite, which is a potential radiation emitter this fact was expectable.

The spots of radiation follow the same direction in both maps.

5.3 Case study C

Case study C is relative to direct underground total gamma radiation measures.

The variograms (Figure 23) generated were fitted to the spherical model. The values from this case study do not fit into the spherical model, however they would not fit into any model as the problem is low quantity of information. Therefore, this study can be considered a first approach. Later on, it would be advisable to do some total gamma radiation studies trying to explore the underground environment of Paranhos.

The variograms follow the direction that had better express the chosen model.

Both maximums (XIV and XVI) and minimums (XV and XVIII) are in coincident areas, despite the values are not the same, the greatness order is the same. Maximums: **450** and **750** cps, minimums **50** and **40** cps, at 1m to ground and close to ground respectively.

At this phase was used other type of equipment (GAMMA SCOUT®). This equipment measures dose rates of radiation, classified earlier as indirect radiation measurements. It is necessary to have in mind that total and gamma radiation dose rates depend on several facts as the weight of the exposed organism, the isotope that is emitting it, among other facts. The division of case from study D and E was made attending to the type of measurement: Surface (case of study D) and Underground (case of study E).

5.4 Case study D

Case study D is relative to indirect surface total and gamma radiation dose rates measurements.

The spatial analysis of the data made with resource to the geostatistical software package named Surfer 8. Both variograms (Figure 45) generated were suitable to the spherical model. The variograms follow the direction that had better express the chosen model. At this study in gamma radiation dose rate was made a division as the maximum for gamma radiation dose rate(1) was **23,46** µSv/h, this was considered an overflow from the equipment and therefore analysis were made without this value: gamma radiation dose rate(2). In this second study the measured maximum was **4,97** µSv/h (XVIII*) and it was measured at Centro Regional de Sangue do Porto. The maximum from total radiation dose rate was **2,47** µSv/h (XXI). Both minimums were measured at IPO: **0,12** (XX) and **0,13** (XIX) µSv/h, total and gamma radiation respectively (Figure 33 and Figure 34).

The measurings made with the device GAMMA SCOUT® gave rise to some kind of controversy. In some of the cases, the value relative to gamma radiation dose rate was superior to the value corresponding to the same place for the total radiation dose rate. This factor was properly confirmed with the use of two machines and it was kept. This point could be justified with the statement that this device needs a longer time to collect several gaps of data giving the necessary time to stabilize the equipment.

5.5 Case study E

Case study E is relative to indirect underground total and gamma radiation dose rates measurements.

The spatial analysis of the data was performed with resource to the geostatistical software package named Surfer 8. Both variograms (Figure 46) generated were suitable to the spherical model. The values from this case study do not fit into the spherical model; however, they would not fit in anyone concerning the low quantity of information. Therefore, this study can be considered a primary approach. Later on, it would be advisable to do some total gamma radiation studies to explore the underground environment of Paranhos.

The variograms follow the direction that had better expressed the chosen model.

Such as in the case of study C in this case higher levels of total and gamma radiation dose rates were measured at Mananciais do Porto. Both maximums: **4,01** (XXIV) **2,23** (XXII) and µSv/h, were measured at this sample site; total radiation dose rate and gamma radiation dose rate respectively. However minimums from case study E: do not coincide with the ones from Case study c (XV and XVII). At the present case study, minimums were measured at subway station Combatentes: **0,19** (XXV) and **0,18** (XXIII) µSv/h total radiation dose rate and gamma radiation dose rate respectively.

This case study is pointed as a primary approach as the quantity of values collected in underground environment was not very GISnificant: 14 values.

Therefore, it would be advisable in the future do other campaigns using both equipments trying to explore Paranhos underground environment.

As we can see through the generated maps the values are clearly affected by values from Mananciais do Porto.

The measurings made with the device GAMMA SCOUT® gave rise to some kind of controversy. In some of the cases, the value relative to the dose of gamma radiation dose rate was superior to the value corresponding to the same place for the total radiation dose rate. This factor was properly confirmed with the use of two machines and it was kept. This point could be justified with the statement that this equipment needs a longer time to collect several gaps of data giving the necessary time to stabilize the equipment.

5.6 Overall analysis

In case studies A1, A2 and B maps representing measurements close to ground show high level of total gamma radiation. Therefore, soils must have in their composition radioactive components or materials that absorb radiation and emitting it later. As an example of this, we have granite that normally is a radiation emitter and is one of the most representative materials in Paranhos sector.

On case study D the map representing total radiation dose rate is the one with higher levels of radiation which was expectable once in this one were measured three kinds of radiation: alpha beta and gamma. Despite this fact, some measures did not reflect this assumption and gamma radiation dose rate was higher than total radiation dose rate. We can conclude that the used equipment needs a longer time to collect several gaps of data giving the necessary time to stabilize it.

Both case studies D and E representing underground measurements are gathered primary approaches, as the quantity of collected values is not important. However, we can establish that Mananciais do Porto have a great influence in all interpolated data, as the values are higher when compared with the universe of the data collected. Therefore, later it would be advisable to do radiation and radiation dose rates studies at Paranhos sector exploring its underground environment.

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Appendix

7 Appendices (on CD-ROM)

Appendix 1. Sample Sites List

Appendix 2. Radiation Units Conversion

Appendix 3. Radiation Measurement units/Legal Limits

Appendix 4. Registration forms From Gamma Radiation

Appendix 5. Registration forms from Total and Gamma Doses of Radiation

Appendix 6. Organized Data from Measurements with Scintillometer SPP2

Appendix 7. Organized Data from Measurements with Gamma Scout

Appendix 8. Conversion Table used with Scintillometer SPP2