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ASSESSMENT OF SUBSURFACE WATER SOURCES IN ISLAND OF SANTIAGO– CABO VERDE WITH EMPHASIS IN SPATIAL DISTRIBUTION OF RADON CONCENTRATION

Thesis

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Budapest, 2020

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ABBREVIATIONS

AdS – Águas de Santiago
STC -ASS – Santa Catarina **-** Assomada (Santa Catarina)
ANAS- Agência de água e Saneamento
CAS - Código de Água e Saneamento
RGS -CV – Ribeira Grande de Santiago **-**Cidade Velha
CA – Ancient Complex Eruptive of Pico de Antonia
CPM – Count Per Minute
DMM / EM1– Enriched Mantle
DW - Distillate Water
FUN – Fundura
INDC - Intended nationally determined contributions
IF DW- Instafluor Distillate Water
HIMU - High μ
MORB - Mid Ocean Ridge Basalts
PA – Pico de Antonia
PLENAS - Plano Estratégico Nacional de Água e Saneamento
PANA-II - Plano de Acão Nacional para o Ambiente II
PEDS – Plano Estratégico de Desenvolvimento Sustentável
PR – Praia
PMT- Photomultiplier tube
SD – São Domingos
NASA- National Aeronautics and Space Administration
SLO – São Lourenço dos Orgãos
SSM - São Salvador do Mundo
SC – Santa Cruz
SMG – São Miguel
RBA – Ribeira da Barca
TAR – Tarrafal
OO DW- Optifluor Distillate Water
WMAP- Wilkinson Microwave Anisotropy Probe
WHO – World Health Organization

1. ABSTRACT

Santiago Island is characterized by scarce hydrological resource, low and irregular precipitation. The island has 9 municipalities that have major dependence on underground water (e.g. springs, wells and boreholes), thus the groundwater is an extremely important source of water in Santiago since the surface water is not stable or even in some period existent. There is no data on radon water resources in Cabo Verde, an island highly vulnerable concerning water resource. The methods applied for measuring the subsurface water for this study are the in-situ measurement for pH, electroconductivity and temperature, and the ex-situ measurement on 29 sampling points across the island, where water was collected on vials filled up with 10 ml cocktail, Optifluor O and Instafluor and for analyses the LSA technique was used. The sampling of water was conducted during one week and after, transported with smallest possible time between sampling and analysis procedure in order to explore the spatial heterogeneity of radon concentration, electric conductivity and pH of subsurface water sources across the island and to try to find relationships with environmental factors.

The results from 29 sampling locations measured showed a low level of radon concentration in water, and those values differ for each geological formation, wherein the highest value found is 59.85 Bq/L ± 9.5 at Conglomerates ante Flamengo geological formation. This formation is of submarine volcanic origin present in the center and south of the island, overlapping with Ancient Internal Eruptive Complex which can be found spread across the island. Sao Salvador do Mundo and Sao Miguel city showed to have the highest average [222Rn] 25.53 Bq/l and 28.76 Bq/l respectively. The non-parametric test was used, and it showed that the spatial distribution of radon concentration does not seem to follow a definite spatial pattern for a specific type of rocks, since different concentration of radon is found side by side or on the same geological formation. The p value indicates to not reject the hypothesis that radon concentration is not homogenous across the island and there can be an association between rock type and physical properties of the environment. The *in-situ* measurement results showed increased salinization across the island especially on the

coastline, varying from the absolute value of 375 µS/cm to 1775 µS/cm and the average of 929.64 µS/cm, the average pH of 10.77 and the average temperature of 27.66 ^{0}C.

2. INTRODUCTION

Water-related issues are a worldwide researched topic not only in environmental sciences with focus on diverse areas such freshwater reservoir, water pollution, sustainable management of surface and groundwater sources or water quality. It's because water is not just essential to quench thirst and to protect health, but it's vital as building block of life, crucial to maintain the economic, social and human development. Nowadays, every country is addressing more attention on different environmental problems according to their own reality, by enforcing political frameworks and regulations, adopting international standards and investing on public awareness, often including water issues.

In Cape Verde the main environmental problems are related to soil erosion and water scarcity due to insular characteristic and the geographic positioning. According to (Carreira *et al.*,2010), there are four (4) critical sectors particularly sensitive such water, agriculture, forestry, and coastal development. The increased water salinization and drought has been identified as the greatest constraint since the country is located in the tropical Sub-Saharan dry region and the yearly average rainfall is very low, resulting in a chronic shortage of water.

The assessment of subsurface water sources in the island of Santiago, with emphasis in the spatial distribution of radon concentration, was chosen during one lecture about water resources and the challenge of its sustainable management in Cabo Verde under the course of environmental sampling II. During this presentation it was explained the regulations of drinking water for human consumption, the different water sources and how the quality of water is controlled by the water authority, and subsequently many others water related issues were discussed, closely related to my work experience in environmental system management at the main water supplier at Santiago Island.

At the end of the presentation, two main questions emerged: (1) why there is no monitoring of radon in groundwater as in other Macaronesia countries and (2) could the type of geological formation be correlated to the radon concentration at island of Santiago? With those questions in mind, I decided to further investigate the subsurface water for drinking consumption at Island of Santiago with emphasis on spatial distribution of radon concentration, in partnership with the national water and sanitation agency in Cabo Verde (ANAS – Agência Nacional de Águas e Saneamento) and the Santiago's main water supplier (AdS - Águas de Santiago. S.A).

Water source is a critical sector, characterized by scarce hydrological resource, low and irregular precipitation in time and space (Santos, 2016). As others countries, Cabo Verde follows the World Health Organization, standards, and have adopted national water policies which defines the fundamental principles applicable to water resources and establishes its preservation, quality, sustainability and rational use taking into consideration its own economic, social and environment reality. Policies such as the Water Code (CAS, 2015), the National Strategic Plan for Water and Sanitation (PLENAS, 2015) and the Water Quality for Human consumption regulation (2015) are followed by the water suppliers and supervised by the National Water and Sanitation Agency.

Santiago island has 9 municipalities which are independent and autonomous for water resources management wherein the majority depend on underground water (*e.g.* springs, well and borehole) stored on tank reservoirs. The capital – Praia and some neighbor city such as São Francisco, São Domingos are supplied mainly by desalinization process of sea water source for public use. In this context the groundwater is an extremely important source of water in Santiago, as the surface water is not stable or even in some period existent, and due to the over exploration for agriculture it has been decreasing gradually especially in the last 5 years according to Chief of Agency of São Miguel (E. Fontes., 2019, *pers. comm.*, 30 August).

Concerning natural radiation with a significant mobilisation in geological systems, radon has received special attention in water supplies worldwide because of its radiation- induced public health hazards. This research topic is important for Cabo Verde because only few studies investigated natural radioactivity, and specifically radon concentration in water has not been studied yet. For example, there is one (1) important PhD research about natural radioactivity where the uranium thorium and potassium in rocks was quantified, as well, radon concentration measured indoors in different locations in Praia at island of Santiago by

(Victória, 2012). The national regulation for drinking water quality have 3 types of routine control, which do not include radon monitoring, and the type of routine control carried includes coliform bacteria, E. coli, smell, electroconductivity, color, residual disinfectant, pH, taste, temperature and turbidity. Furthermore, the geology of the Island of Santiago is ideal for this present study: (1) public water sources used for service and drinking purposes, are primarily from springs and wells at high elevations; (2) the variability in geological formations is significant to induce an appreciable spread in dissolved radon concentrations.

This first investigation of subsurface water radioactivity can be used to identify current knowledge gaps in order to enhance the public awareness and national authorities; it also will allow a more deeper radioecological research in the future, perhaps its monitoring considering its implication on human health and on the ecosystem.

2.1. Aim

The main aim of the thesis are the following: to explore the spatial heterogeneity of radon concentration, electric conductivity and pH of subsurface water sources, their distribution across the island and to try to find relationships with environmental factors. Beyond the radiological issues of radon concentration, the distribution of radon in subsurface water sources can be an indicator for environmental processes like water mixing of oceanic and meteoric origin, and some properties of the subsurface water flow system in the island.

2.2. Hypothesis

Radon concentration is not homogenous across the island and there can be an association between radon concentration, rock types and physical properties of the environment.

3. LITERATURE REVIEW

3.1. Sources of natural radioactive radiation

Natural radioactive radiations originate from many sources, including more than 60 naturally occurring radioactive isotopes found in rock, soil, water, and air and the maximum contributions to these invisible radiations originate from the decay series of 238U, 232Th and the singly occurring isotopes like 40K (Alonso *et al.* 2019). Thus, natural occurring radioactive materials have always been present within the earth's crust and are present in all biota to varying degrees.

The distribution of naturally occurring radionuclides mainly 238U, 232Th and 40K and other radioactive elements depends on the distribution of rocks from which they originate and on the processes through which they are accumulated and concentrated. Radium and its ultimate precursor uranium in the ground are the source of radon, the α radioactive inert gas. As an inert gas and having sufficiently long lifetime (3.8 days) it can move freely through the materials like rock, soil, sand, etc. Short lived radon progenies have been established as causative agents of lung cancer. Radon appears when radium (226Ra), a 238U-family division product, decays (Subaihi, Harb & Abdullah, 2019).

As it is known, the first recorded awareness of the effects of the environmental radiations on human was reported by Agricola for metal (silver, lead, zinc, cobalt, iron),uranium miners in the Erz mountain of eastern Europe in 1556, later was discovered that radon is the primary cause of lung cancer in miners. With the discovery of radium, it was recognised that all soil and rocks emitted alpha, beta and gamma radiation from uranium, thorium and other natural radioactive elements in the earth crust. (Markich & Twining 2012).

Radionuclides which can be found in the environment can be divided into three groups:
I. Naturally occurring nuclides of very long half-life which have persisted since the formation of the earth (Primordial or terrestrial), and their shorter-lived daughter nuclides.

II. Naturally occurring nuclides which have short half-lives on the geological time scale, but which are being continuously produced by cosmic-ray radiation (Cosmogenic).

III. Radionuclides released into the environment due to man's activity and accident (Man-made or anthropogenic) (Gadallah, 2009).

Radioactivity is a natural phenomenon that occurs when atomic nuclei in higher energy states achieve greater stability by emitting energy in the form of radiation. The nature of radiation is essential for the management of the interaction on the environment for radiological control (Csanád, 2012).

3.1.1. General properties of radon.

Radon is a radioactive noble gas of a natural origin, produced by the radioactive decay of uranium, thorium that may be found anywhere in soil, air and in different types of water: surface, well and spring. It is created during the chain decay of ^{238}U, ^{232}Th and has two main isotopes, such ^{222}Rn, ^{220}Rn with the following decay chain:

- ^{222}Rn with half-life $T_{1/2}$= 3.82 days and its short-lived decay products: ^{218}Po,^{214}Pb,^{214}Bi,^{214}Po,^{210}Pb,^{210}Bi,^{210}Po called part of the Uranium series.
- ^{220}Rn with half-life $T_{1/2}$= 55.6 seconds, also called thoron, and its decay products: ^{216}Po, ^{212}Pb, ^{212}Bi, ^{212}Po, called part of the Thorium series (Victoria, 2012).

The radon gas may enter natural waters by two main processes, by in-situ alpha-decay of its parent nuclide, ^{226}Ra, dissolved in the water (local radon), and by emanation from neighboring underground air, gas and solids (environmental radon) (Somogyi & Lénárt, 1986).

3.1.2. Radon in Cape Verde

The isotope with more interest to be studied is ^{222}Rn due to its longer half-life and radiological protection, and it occurs more on rocks, soils, water tend to appear on ground floor in varied concentration (Pereira *et al*. 2001; 2003). There is an extensive research on the Island of Santiago related to groundwater assessment, water resources, hydrogeology and hydrochemistry in order to understand the influence of the anthropogenic activities on the water and the main origin of its salts, as well the main type of water pollution, (Pina, *et al*.,2005; Carreira, *et al*.,2010; Carreira *et al*.,2019).

According to (Pereira, 2010) in his PhD thesis about the strategy for the geoconservation on the Island of Santiago, tried to explain the geological history of the Cabo Verde archipelagos basing on magmatic composition which allows to characterize three types of volcanism, one type of them is the chemism magnetism identified at Island of Santiago and Maio. This type of magmatism presents pillow lavas type MORB (Mid Ocean Ridge Basalts).

He emphasized that lavas observed from the east of the island of Tenerife show a clear trend towards an enriched component, HIMU, similar to the basalts of Cape Verde (Abratis *et al*., 2002 *apud* Pereira 2010) which corroborate the idea of (Widom *et al.*,1999 apud Pereira, 2010) that the basaltic and carbonaceous rocks of Cabo Verde presents High μ (one type of magmatic reservoir component, and the name is derived from the value of $\mu = {}^{238}U / {}^{204}Pb$, since it has a high μ content and, in general, for the Pb isotopic ratios) similar of Canary island, this fact allowed to establish a comparative line between Açores archipelago and Cabo Verde Islands. The same research based on others studies such (Doucelance *et al*., 2003) about isotopic variation on basaltic rocks on Cabo Verde with others oceanic island showed that they are a mixture of magmatic material from different origin of reservoir such as DMM, EM1, HIMU.

There are studies carried out on oceanic island (Alonso *et al*., 2019) especially on Eastern Canary Islands (Gran Canaria, Fuerteventura and Lanzarote) wherein it was concluded that areas in which intermediate or acidic volcanic and plutonic rocks predominate were characterized by greater radon activity concentration in soils. Another study carried out on La Palma Island (Canary Islands) in order to determine the normal levels of radon gas in soils and in the underground environment concluded that in general the radon level values are low, both at the surface and in the underground, although weak anomalies were detected into a gallery in the north of the island (200 pCi/l) and at the southern rift (>180 pCi/l); (Marttin *et al*., 2003). Based on these ideas, it is interesting to see others scientific findings on the Macaronesia region, related to radon occurrence and its concentration level in the environment.

3.2. Natural Conditions at the Island of Santiago

Santiago is located in the South-eastern part of Cabo Verde archipelago about 400 miles (640 km) off the West African coast. It is the largest of all islands, occupying an area of 991 km^2, approximately a quarter of the total area of the archipelago (4033 km^2) (Goncalves, 2015).

Figure 1 - Geographic map of Cabo Verde Island on the north Atlantic Ocean, adapted from Carreira et al.,2010

Its location occupies the southern tip of the archipelago, between the parallels 17º 30' and 15º 00' north latitude and the meridian 22º 30' and 25º 30' west longitude. It has a slim shape in the North-South direction, with a maximum length of 54.9 km, bounded to the North by Ponta Moreia and to the South by Ponta Mulher Branca. Its maximum width is 29 km and is bounded by Ponta Janela, to the West and Ponta Praia below, to the East. The land rises to its highest elevation at Pico de Antónia, 1,392 meters above sea level (Goncalves & Santos, 2018)

The country presents climatological and hydrogeological features typical of Sahelian regions where the seasonal changes are related to the Inter Tropical Front (ITF), meaning that this atmospheric circulation over west Africa makes the climate dry to semi- arid, influenced by an oceanic effect characterized by a strong desiccant and erosive action on the archipelago which may cause precipitation on the slopes exposed to the northeast (Lélé & Lamb,2010).

The Chairman of the Board of Directors of ANAS (Agência de água e saneamento), considered that the country is facing water crises with a significant reduction of water availability and low underground storage capacity, he explained that the main surface water reservoirs (Dam) are in a very low water volume, adding as well that the borehole, well, and springs are extremely insufficient comparing with historical values (ANAS 2018).

Due to the localization of islands of Cabo Verde, the climate of the study area, the Island of Santiago is strongly influenced by the masses of warm, dry air from Africa namely the Sahara Desert. (Lopes & Santos 2010). Based on the Preparatory Survey Report on the Water Supply System Development Project by JICA, the island is characterized by scarce hydrological resource, wherein the average annual rainfall is 265 mm and the potential evapotranspiration is high. Rainfall is usually very intense and irregular and tends to be concentrated in the months between July and November. In the interior of the island the incidence of rainfall is greater (321 mm/year in Pico da Antonia, altitude about 1,390 m) than on the coastline (170 mm/year in Praia). The temperatures fluctuate throughout the year between minimum value 22^0 C at February and the mean summer season maximum 27^0 C at September (JICA,2011).

According to national plans conducted by the General Directorate for Environment of Cabo Verde, on diverse are such as climate change, biodiversity conservation, combat against desertification, PANA-II, recently PEDS, and INDC , reports that Cape Verde islands are vulnerable to climate change, in particular the coastal areas, with high population levels and economic investment, including port facilities, airports, trade, tourism and agriculture.

The Government recognizes the need and the high importance of adopting integrated environmental policies to ensure the sustainable management of environmental resources (PEDS, 2017-2021).

Related to biodiversity it is assured in the Constitution of the Republic in articles 7 "Tasks of the State" and 72 "Right to the Environment" and other legal provisions. However, some practices resulting from human activities such as: the use of agricultural areas for urban purposes, poor agricultural practices, destructive fishing, inadequate forest exploitation and the introduction of invasive species have contributed to the degradation of ecosystems and the reduction of species and of genetic material (National Strategy and Plan of Action on Biodiversity, 2014-2030).

The ecological value and economic importance of biological resources (plants, animals, lichens, fungi, microorganisms) create and maintain the soil, recycle nutrients, play a critical role on oceanic ecosystem in maintaining the balance of oxygen and carbon dioxide that affects climate and rainfall patterns contribute to plant pollination, serve as biological barriers to soil erosion, and water filter (Massetti & Gil, 2020).

3.3. Hydrology and geological framework of Santiago

According to the study of groundwater assessment of Santiago Island, (Pina *et al*., 2005; Carreira *et al.*, 2019) the water–rock interaction mechanisms is the major process responsible for the groundwater quality (mainly calcium-bicarbonate type), reflecting the lithological composition of the subsurface soil. Also, anthropogenic contamination was identified, in several points of the island. They studied isotopic techniques (δ^2H, $\delta^{18}O$ and ^3H content) combined with geochemistry providing a comprehensive information on groundwater recharge, as well as on the identification of salinization mechanisms (e.g. seawater intrusion, salt dissolution, and marine aerosols) of the groundwater systems, at Santiago Island. Their groundwater sample showed as NaHCO3 type on high altitudes and the majority of samples with high salinity are on the valleys where the intense agriculture is practiced together with excessive pumping of the subsurface water. On the coastal area the samples showed high Na and Cl content indicating seawater intrusion as the main mechanism responsible for the groundwater salinity. The study did not find a realistic explanation for high concentration of Na, at the same time having low salinity value. They tried to explain from the weathering of plagioclase but the chemical analysis of rock samples from different geological formations showed Na2O percentage varying 1.19 and 2.79, thus, another source of increase in Na should be investigated.

Another study carried by (Goncalves, Valente & Grande, 2015) analyzed the water quality in a small city Sao Domingos at the Island of Santiago showed that the water presents a mineralized nature with an average electrical conductivity of 1361 µS/cm. According to the hydrochemistry they classified the water based on 2 type: mixed (bicarbonate and chloride) and mixed with sodium. The study found that, considering what is established for water quality in the Cape Verde and Portuguese legislation, only 36 % of the water samples are eligible for human consumption. Regarding irrigation use, approximately 68 % of the samples present high-to-very-high salinization risk.

The cause for groundwater salinity at Santiago Island has influence also on natural salinity boundaries exist in aquifers due to the natural geological factor controlling the maximum

depth of circulation, and also the interface between marine and fresh water (Carreira *et al.*,2019). The climatic factors play an important role, and a continuous low rate of recharge in arid areas, lead to a widespread salinity of groundwaters. The anthropogenic contamination is critical for the increase of groundwater salinity because of over exploration of groundwater table by pumping without proper monitoring system and the practice of intense agriculture. Other factors such as the removal of the native vegetation may cause the rise of regional water tables promoting leakage of saline from underlying aquifers (Carreira *et al*., 2010). For point of reference the Atlantic Ocean, on average is the saltiest major ocean
belonging to the western North Atlantic Central Water (WNACW) which have 35.0 – 36.7 part per thousand salinity and the maximum salinity values occur in subtropical regions with low rainfall and high evaporation, where Cape Verde Island are situated (Wikipedia, 2020).

3.3.1. Geological history of Cape Verde Islands

Cape Verde Islands are volcanic in origin, the archipelago's oceanic basement formed during the Late Jurassic and it is generally assumed that the islands originated with the development of hotspot activity above a mantle plume. Cape Verde appears to be composed of the oldest rocks in Macaronesia (Brown *et al.*,2009*).* Soils are mainly of volcanic origin, they originated from volcanic rocks like basalts, phonolites, trachytes, andesites, tuffs, slags, and sedimentary rocks—mainly limestone. Despite the small size of the archipelago and the similarity of the parent material, a wide variety of soils are present in Cape Verde and reflect its microclimatic and topographic diversity (Pereira,2010).

According to (Pinto *et al*., 2014) the $^{40}Ar/^{39}Ar$ data indicate that the volcanic evolution of Santiago spread from 4.6 Ma (the major submarine phase) to 1.1-0.7 Ma (the late volcanic activity), with most of the sub aerial volcanism taking place from 3.3 to 2.2 Ma. The periods of intense volcanic activity, which caused the growth of the island, are separated by erosion and sedimentation periods, materialized by intercalated sedimentary formations. After the initial phase of submarine volcanism, the volcanic building emerged and the volcanism became sub aerial.

The first geologic descriptions in Santiago (Teixeira, 1950 *apud* Pereira 2010) indicated that the Island was constituted exclusively for magmatic rocks. But observation made during the geologic mission in Cape Verde by Antonio Serralheiro in 1976, wherein he did an exhaustive study about the geology of Santiago. Later came to confirm that there is a presence of sedimentary rocks in a greater proportion than previously assumed to exist. However, due to their representativeness, they are not an essential element in the geology of the island (Moreira, 2009). The region with the highest occurrence of sedimentary strata is Tarrafal, in the northern part of the island. Next to the pier at Praia do Tarrafal, fossiliferous limestone sandstones and conglomerates, typically coastal, emerge. Metamorphic rocks are practically non-existent. (Pereira,2005).

Table 1

The major lithology types in the Island of Santiago

Rock type	**Surface Occupied (Km^2)**
Basalt and pyroclastic products	909
Limburgites	57
Leucitites e Nephelinites	1
Tefrites	1
Limestone	3
Other Rocks	3
Total	**991**

Note: Adapted from Serralheiro, 1976 *in* Victória, 2012

The main investigation on geology of Santiago allow to establish stratigraphic sequence starting for the old formation to more recent formation:

- ✓ Ancient Internal Eruptive Complex (CA)
- ✓ Flamengos Formation (λρ);
- ✓ Orgãos Formation (CB)
- ✓ Pico da Antonia, basalt- basanitic (PA)
- ✓ Pico da Antonia, trachyte-phonolitic (PA)
- ✓ Assomada Formation (A)
- ✓ Monte de Vacas Formation (MV)
- ✓ Recent Quaternary Age Sedimentary Formations

Table 2 describes the stratigraphy with more details, different formations, environment and period.

Table 2

Summary about the stratigraphy of Santiago

Formation	Terrestrial facies	Marine Facies	Period	M.a
Recent Quaternary Age sedimentary formations	Alluvial dunes, slope deposits and flash flood, Terraces	Beach sands and gravel	Holocene Pleistocene	
Monte de Vacas Formation (MV)	Slag, pyroclasts cones, and small associated strokes		Pliocene	
Assomada Formation (A)	Sub-aero mantles and pyroclasts			
Eruptive complex of Pico de Antonia (PA)	E - pyroclasts and associated flows; D - mantles and some levels of interleaved pyroclasts; C - breach tuff (TB); B - phonolites, trachyte and similar rocks - Sediments of undetermined position A - thick series essentially of mantles and some levels of pyroclasts	Conglomerates and calcarenites, fossiliferous -uppers conglomerates, limestones and calcarenites, fossiliferous - lower mantles and pyroclasts - Conglomerates and calcarenites fossiliferous	Miocene	1.5
Sediments after the Orgãos Formation and before the lower submarine lavas of the PA;	Small outcrops of sedimentary rocks (calcarenites, and fossiliferous calcarenites) in some localities such as in Ribeirão Fundo, Boa Ventura, Monte Vermelho water line			7
Lava formation post Orgãos Formation	Trachyte			
Orgãos formation	Flood deposits, lahar type, with interlaced mantle/robe	Conglomerates, limestones and calcarenites, fossiliferous		
Flamengos formation (λρ)		Mantle and pyroclastic		
Conglomerates Ante – Flamengos Formation		Old conglomerates		
Ancient Internal Eruptive Complex (CA)	- Basaltic lava phases (veins, chimneys and robes); - Phonolites, trachyte and similar rocks (chimneys and lode) - Carbonatites (spikes and veins); - Deep gaps; - Feldspathoid syenites and similar rocks; - alkaline rocks (alkaline gabbro olivenites, alkali pyroxenites melagabros, etc.)-		Ante Miocene	26

	'Filoniano nature complex essentially basaltic			

Note: (Alves *et al*., 1979, *apud* Pereira 2010)

The volcano- stratigraphic sequence, was first reported by Serralheiro (1974), and later improved by Matos Alves et al. (1979), which has been used as the basic support for hydrological and hydrogeological resources research (Pereira, 2010).

The main geological formation on the island of Santiago have the following characteristics:

Recent Series - Quaternary, consisting of the Monte das Vacas Formation formed by cones of pyroclastic material with some associated lava flows, and very permeable. For this reason, it does not allow the retention of the water that infiltrate but it goes toward the main aquifer.

Intermediate Series - Mio - Pliocene, constituted by the Eruptive Complex of Pico da Antónia, formed by subaerial basalt robes with interleaved pyroclastic material and robes submarine basaltics, forming a stack of greater thickness and greater extent of the Island from Santiago. It's the main and most important aquifer system.

Base Series - Ante - Miocénico, constituted by the Ancient Internal Eruptive Complex, with Flamengos formation and Conglomeratic Formation - Brechoid. This series is very compact less permeable.

The most important reservoir of fresh water is the PA formation presenting terrestrial and submarine facies (Pillow-lavas) (Carreira *et al.*, 2010).

The eruptive complex of Pico de Antonia is the largest development in the island, occupying more than half of the surface of Santiago, wherein the CA, the oldest formation cover the centre and the south part of the island, and Flamengos formation the east part of the island. Orgãos formation is found on Orgãos area and at coastal area.

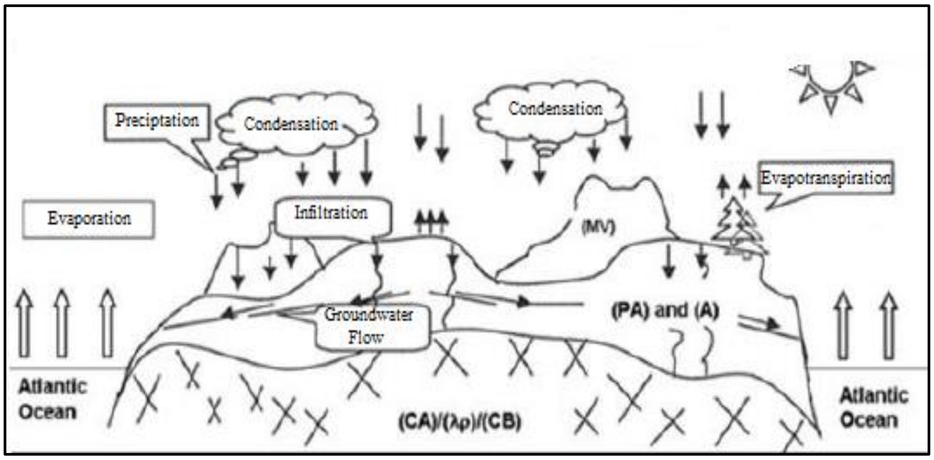


Figure 2- Schematic NW–SE cross section displaying the hydrogeological conceptual model of Island of Santiago (Paula M. Carreira et al. 2010).

4. METHODOLOGY

4.1.Study area

The Island of Santiago has nine (9) municipalities: Praia, Ribeira Grande de Santiago - Cidade Velha, São Domingos, São Lourenço dos Orgãos, São Salvador do Mundo, Santa Catarina, Santa Cruz, São Miguel, Tarrafal (Pereira 2010). The sample locations (Figure 3) and their geographical references are given in table 1 of the Appendice.

According to (Pina *et al*., 2005) the hydrological balance shows that the rainfall that falls on the islands shows that, 67% evaporates, 20% flows in the form of surface runoff and just 13% recharge aquifers.

Underground Water Resources are estimated at 124 million cubic meters per year. Of that total amount, only 65 million cubic meters per year is technically exploitable, in a year of regular rainfall, and 44 million cubic meters per year, in periods of Dry (Shahidian, 2015).

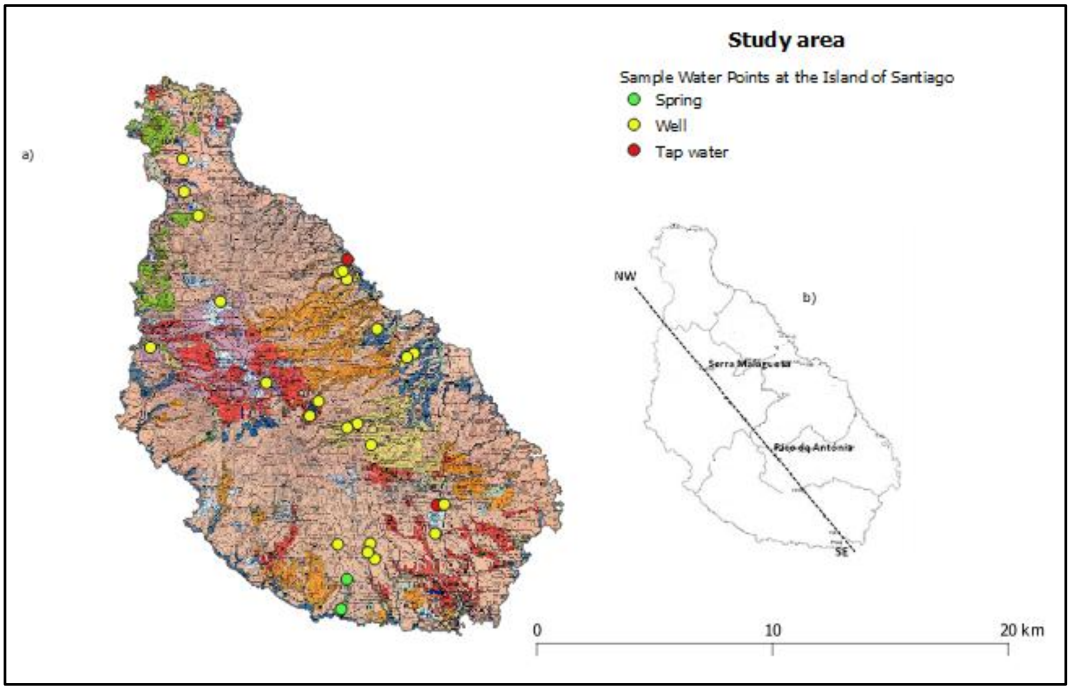


Figure 3 - (a) Geologic map displaying the sample points across the Santiago island, covering the different geologic formation on the island; (b) Schematic cross section NW- SE of the island, shown in Figure 2. Source: Image created on QGIS based on the geologic map with scale 1:100 (own work)

4.2. Material and method

The study was based on qualitative and quantitative methodology using archive review of previous work done with natural radiation measurement in Cape Verde, water policies and international documents for contextualization in order to understand how the topic is approached and its pertinence globally.

International articles were revised with special attention on the Macaronesia region (Azores, Madeira, Savage Islands, Canaries, Cabo Verde), which according to (Palacios *et al*., 2010) present biogeography similarities and all are volcanic archipelagos.

Different national entities were contacted to explore the topic in order to know the level of knowledge about natural radioactivity with emphasis on radon (^{222}Rn) and its importance to be studied on drinking water at the Island of Santiago.

It is based also on unstructured interview with different persons such as hydro chemist (National Water and Sanitation Agency, geologist of Cape Verde University, managers of water and sanitation supplier to understand their point of view about natural radiation of water sources in Cape Verde as a new important concept that can be considered.

The quantitative methodology was based on the sampling of subsurface water on water points such as wells and springs in nine (9) municipalities covering all lithological formation across the island. The pH, EC, temperature was measured *in situ* and the water collection for radon concentration were carried out using prepared vials and cocktails for *ex situ* measurement using the Liquid Scintillation Analyzer (LSA) technique at ELTE Budapest.

a. **Selection of the measurement points**

After preparing the field work plan with the technical assistance provided by ANAS, the original points provided by the main water supplier (AdS) was reviewed and rearranged accordingly to the accessibility, workability and the importance for the community supply. The sampling process was carried out during 3 days (28th, 30th August and 2nd September).

On 28th August the sampling procedure was done on five different municipalities: Praia (Monte Vaca), Ribeira Grande de Santiago (Cidade Velha), São Domingos, São Lourenço dos Orgãos, São Salvador do Mundo.
On 30th August the samples were collected on Santa Catarina, Tarrafal, and
on 2th September on Santa Cruz and São Miguel.
Some of localities have less representativity (2 points) due to the difficult access and inactive wells, especially on São Lourenco dos Orgãos and São Salvador do Mundo. The westernmost part of the island has one point because the others reservoirs are in mountainous parts. The distance between sampling points varies from a ranging of 0.13 km to 4 km inside within one locality.
The criteria were used to choose the sampled points, geographical distribution and representativity and, where there were possible to sample, which all geological formations on the island were included in different localities. Even tough the west part of the island of Santiago has less representativity due to difficult access areas (Ribeira da Barca), the total sample points are 29 sites (2 springs, 2 houses from tap water, 25wells).

The sites sampled have different characteristics from each other, vary from place to place according to the point availability for water collection, preferring the closest as possible to the origin of water from well and spring. During the sampling, the water was collected in many ways: from drinking fountain through the pipework, on the pumping houses machine through a vents single function, pipe feeder to reservoir tanks, tap water which was the most closely connected to the well (this because from the pumping house machine there were no available point).

b. **Sampling procedure**

Radon is a very mobile gas and can escape easily during sampling procedure and transportation, thus, it needs to use an adequate, careful sampling and analytical methods to determine the ^{222}Rn concentration in water.

During the sampling procedure it was used a plastic bottle, syringe (12ml) or bailer to collect the water from different points and vials filled up with 10 ml cocktail. The pH, Electroconductivity and Temperature was measured in the spot using PCtestr 35 multiparameter device (a property of the Department of Geography at ELTE), wherein for each measurement KCl solution calibrations were carried out.

The water was sampled in different ways to the syringe: on site to a syringe and to the vial, on site to a bottle and then to the vial, using syringe from open surface water or using syringe from a pipe, and with the bailer to a syringe. The average time taken to collect the water and prepare the vial was 2 minutes (sampling report at the Appendice table 4).

For the radon analyses we used two different cocktails: Optifluor O and Instafluor 10 ml. In addition, 10 ml of water was collected into the vials, after it was sealed with parafilm, each one marked on cap with initial of the area and the code well and spring. The flushing time of the points was 2 minutes to avoid the collection of stagnant water. The depth of well varies very much according to the water availability. According to Carreira *et al.*, 2010 the water table with available water on PA formation is around 300 m depth. The depth of the wells sampled vary from 30 m - 300 m.

The Figure 3 shows the details about the sampling procedure on different site with different type of material collection.

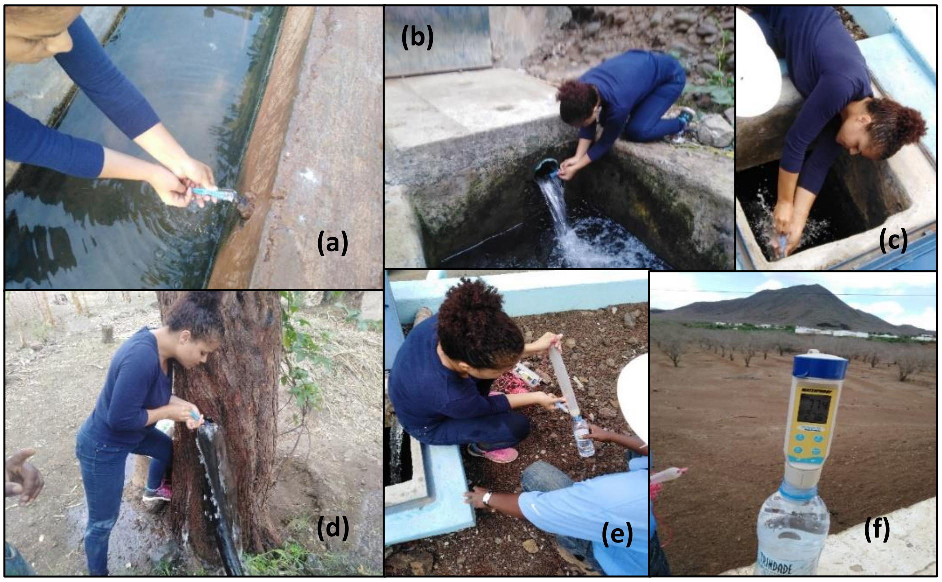


Figure 4- The sampling procedure, using different methods from different medium at different sites. **(a)** Salineiro Drinking fountain, the sampling site, where the water was collected on site to a vial, using syringe from a pipe, wherein the outflowing time was noted (2min). **(b)** The sampling site is a gallery (spring) where the water was collected on the site to a vial, using the syringe from a pipe. **(c)** The water was collected on site to a vial, using the syringe from the incoming water to feed the reservoir. **(d)** The water was collected using syringe from a pipeline directed connected to the well, which is pumped out. **(e)** Water collected using bailer to a bottle and transferred to a syringe, at this point we collected mix water from different origins, which could be interesting for comparison. **(f)** Device used in each sample point to measure pH, Electroconductivity and temperature.

c. Dissolved radon measurement

For the measurement of dissolved radon concentration in water the technique of Liquid Scintillation Analysis was used. The samples were transported to Budapest, Hungary two days after the sampling process where the measurements were done after 1 day.

In this investigation vials and two different of cocktails were used (Figure 5), both of which are complete ready liquid scintillator cocktail for counting non-aqueous samples, it accepts a variety of organic solvents and can also be used for counting biological material, they have high flash point liquid scintillator cocktail, present no diffusion through polyethylene vials.

Scintillator liquid is advantageous to use because it can be mixed with the samples and short-range radiation can be measured (Vial, cocktails).

To determine the number of decays in the samples it is needed to count the number of scintillation processes. For this we used the equipment Tricarb 1000 TR - Liquid Scintillation Spectrometer to determine the count per minute values (CPM).

Inside this device there are two photomultiplier tubes (PMT) which will produce electric signal out of the scintillation light and can count it. The Scintillation photons will hit a very thin beryllium layer; The photons will create a photo effect, which electrons will be ejected out of the layer; photoelectrons will be accelerated in some hundred volts. The dynodes are used as a special metal to shoot out eletrons 10 – 12 dynodes are used. After a scintillation, electric signal is measured and the amplitude is transferred to a PC, where a software constructed a spectra of them.

The amount of the light output (L) is proportional to the number of excited atoms therefore proportional to the energy deposited in the material. The radon concentration is expressed as Bq/l

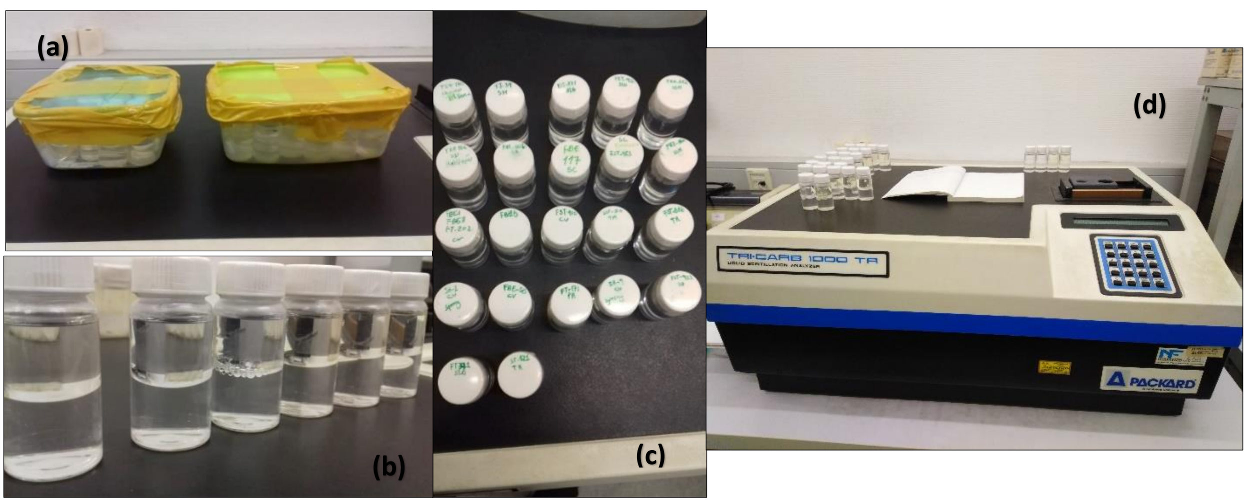


Figure 5 - **(a)** The samples contain cocktail+ sampled water, showing how it was packed and brought for the laboratory measurement; **(b)** the vials showing two (2) different cocktails, lighter color represent Instafluor, and the yellowish is Optifluor; **(c)** The vials are marked on the cap according to the well, spring codes (code number+ locality); **(d)** the device used for counting the photons Tricarb 1000 connected to a computer where the software processes and read the spectral.

d. **Calibration procedure**

The samples were collected on vials with two different cocktails as described earlier on the dissolved radon measurement procedure. Firstly, the device used is TRI- Carb 1000 TR, Liquid Scintillation Analyzer were calibrated using the ^{14}C sample, to set up high voltage and to calibrate the light output.

The (Counts Per Minute) CPM was measured to find the concentration of radon Bq/L in the original time in Cabo Verde. For this purpose, we need to use the calibration curve for each cocktail.

The calibration curve of c=(CPM-B)/slope was used. We applied slope =1.98 value from previous calibrations, and determined the B (background value) precisely for this project. The reason of this was that the concentrations at the measurement time were already quite low, therefore the B value is important. We determined the B for Optifluor O and Instafluor cocktails separately by 99 times 1 hour measurement series.

Table 3

Table summary of calibration procedure

Start	Vial	Cocktail	Average	Variance
September 13	IF DW	Instafluor	10.18	0.45
September 15	OO DW	Optifluor	11.29	0.47
September 20	2003 DW	Optifluor	10.05	0.43

Note: Background measurement performed during 50 times per 1 hour each sample using distillate water with different cocktail, in order to compare the variance / scintillation (DW+IF) (DW+OO).

The preparation of IFC1 and OOC1 was performed in the Nuclear chemical laboratory made by Károly Süvegh, using 10 ml cocktail + 10 ml standard solution (1 Bq/ml):

1. measurement: 100×30 min IFC1 start 16:00 pm January 27
2. measurement: 100x30min OOC1 start 13:23 pm January 31

Table 4

Count Per Minute for each calibration solutions and their results

CMP	Solution	CPM results
CPM1	DW OO	11.29
CPM2	Ra OO	647.29
CPM3	DW IF	10.18
CPM4	Ra IF	644.56

$CPM = a.c$ +b,

C$= \frac{\text{CPM (Sample)} - \text{b}}{\text{a}}$; where **a** is the slope, **c** is the concentration and the **b** is the background.

e. **Scope and limitation**

Sampling and measurement of radon in groundwater are complicated by the high volatility of the gas. A method including sampling techniques, pumping, flushing time, filling arrangement and sample transportation and measurement should be included as uncertainty factors. The water collection was done on wells and springs, therefore, borehole (manmade hole, *poços* in Portuguese) was not included in this study since most of them are inactive or used just for irrigation purpose due to chemical contamination or over exploitation .

The sampling campaign was programed initially to have 2 phases, dry and wet season. It was possible to sample only on dry season due to the lack of precipitation during the year 2019. The sample size (n=29), geographical location, was chosen according to practical reasons such as financial resources and time, therefore there is just one sample per point, which can be a constraint for this preliminary study.

The method for radon measurement was chosen because the technique is available in the Physics Institute at Eötvös Loránd University Budapest, Hungary, and the experience was performed within a subject (Environmental Sampling II) It is aware that there are other methods that could be more accurate such as rad7 for *in situ* radon detector, but transportation of that detector was not feasible. Considering the advantages and disadvantages of the methods of radon measurement in water and the present possibilities, the liquid scintillation spectrometry was chosen.

The time of sampling and transportation till the measurement procedure was taken into account where the correction time was performed using excel spreadsheet ($e^{-\lambda t}$).

The hydrogeology studies are based on literature review of previous studies.

5. RESULTS AND DISCUSSION

Subsurface water samples from wells and spring were collected on August 28th, 30th and September 2th, during three fieldwork campaigns, and the samples were transported back to Hungary after two days for measurement of radon concentration (^{222}Rn), using the LSA technique with Tricarb 1000 device. Electrical conductivity (µS), hydrogen ion concentration (pH) and temperature (ºC) were measured in situ. Hydrology and geological data were available in the framework of previous studies carried out at the Island of Santiago by other authors (Pereira, 2005; 2010; Victória, 2012; Carreira *et al*., 2019). For data processing the QGIS software was used for map distribution and Excel spread sheet for calculations.

5.1. Results for *In situ* measurement

The *in situ* measurement result is presented on table 5

Table 5

Results of in situ measurement

Localities	Code	Temperature	EC	Ph	Time of measurement	Cocktail	Geological formations
PR	FT-171	27.4	773	10	11:22:00	Optifluor	Eruptive Complex of PA
CV	FBE-58	27.8	429	10.2	10:12:00	Optifluor	Eruptive Complex of PA
CV	FBE-1B	28	375	9	09:12:00	Instafluor	Eruptive Complex of PA
CV	FT-202	27.2	421	10	10:30:00	Optifluor	Eruptive Complex of PA
CV	FST-910	28.6	401	10.1	10:47:00	Optifluor	Eruptive Complex of PA
CV	58-1	27.5	458	10	08:15:00	Instafluor	Chimneys, pyroclasts
CV	58-9	27.3	393	10	08:39:00	Optifluor	Eruptive Complex of PA
SD	FBE-53 B	27.9	676	9.8	11:47:00	Optifluor	Eruptive Complex of PA
SD	FBE-156 (tap water)	27.2	716	9.2	12:25:01	Optifluor	Eruptive Complex of PA
SD	FST-922	27.3	868	10.1	11:35:00	Instafluor	Eruptive Complex of PA
SLO	FST-912	28.9	1490	7.8	13:05:01	Optifluor	Dikes chamney
SLO	FT- 371	27.4	1041	8.4	12:47:00	Optifluor	Orgaos Formation
SLO	FST- 871	29.3	1386	8.8	16:16:01	Optifluor	Dikes chamney Pyroclast
SSM	FBE-882	25.6	1093	10.9	13:52:00	Instafluor	Complex Filoniano de base
SSM	FBE-860	27.6	1397	7.4	14:33:00	Optifluor	Complex Filoniano de base
ASS	FBE-117	25.1	589	10	13:57:01	Instafluor	Assomada Formation
FUN	FST-953	26.4	436	11.8	13:20:00	Instafluor	Monte de Vacas Formation
RBA	FBE-170	27.9	1500	12.7	11:46:00	Optifluor	Filoes e chamines
TAR	ST-121	26.4	427	12.2	16:09:00	Optifluor	Eruptive Complex of PA
TAR	FST-886	27.1	536	9.2	16:40:00	Optifluor	Monte de Vacas Formation
TAR	SST-30	27.6	926	12.4	17:02:00	Optifluor	Eruptive Complex of PA
STC	FT- 65	31.1	1335	13.5	10:02:00	Optifluor	Dikes and chamneys
STC	FT- 59	28.3	1095	13	10:46:00	Optifluor	Dikes and chamneys
STC	PT- 33	27.7	1142	12.8	10:55:00	Instafluor	Submarine Mantle Formation
SMG	FST- 814	27.7	1586	13.5	14:05:00	Optifluor	Congl. ante Formation Flamengos
SMG	FBE- 144	27.2	1371	12	14:16:00	Optifluor	Congl. ante Formation Flamengos
SMG	FT- 39	27.5	1775	13.5	14:30:00	Optifluor	Congl. ante Formation Flamengos
SMG	Tap water	29.6	1395	13.3	15:00:00	Instafluor	Dikes and chamneys

Note: The sampling poin displaying the relevante informarion about the geologic formations and the area.

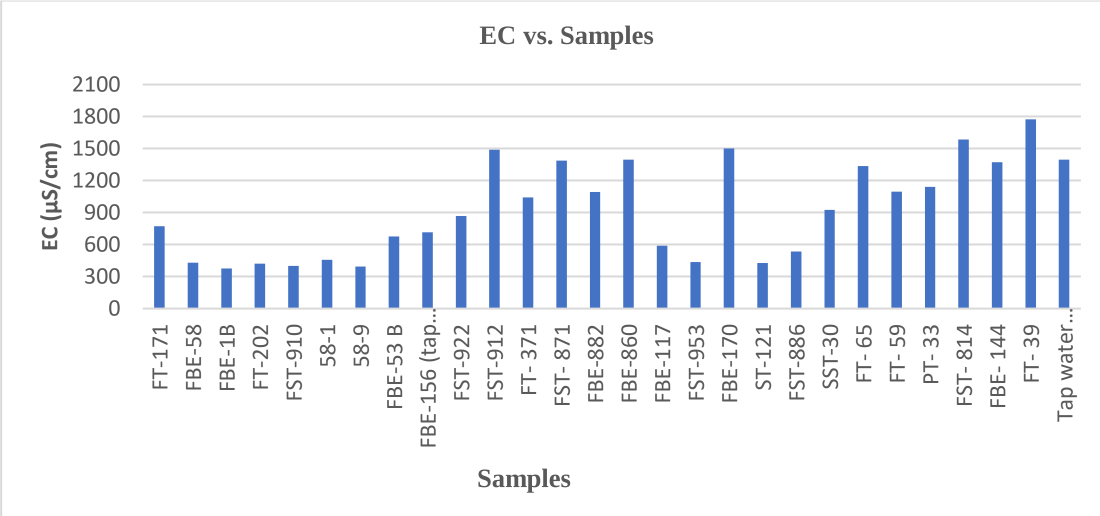


Figure 6 - The graphic shows the Electroconductivity (absolute values) in each measured point across the island, where the highest value tends to appear near to the coastline and the well where water availability is low.

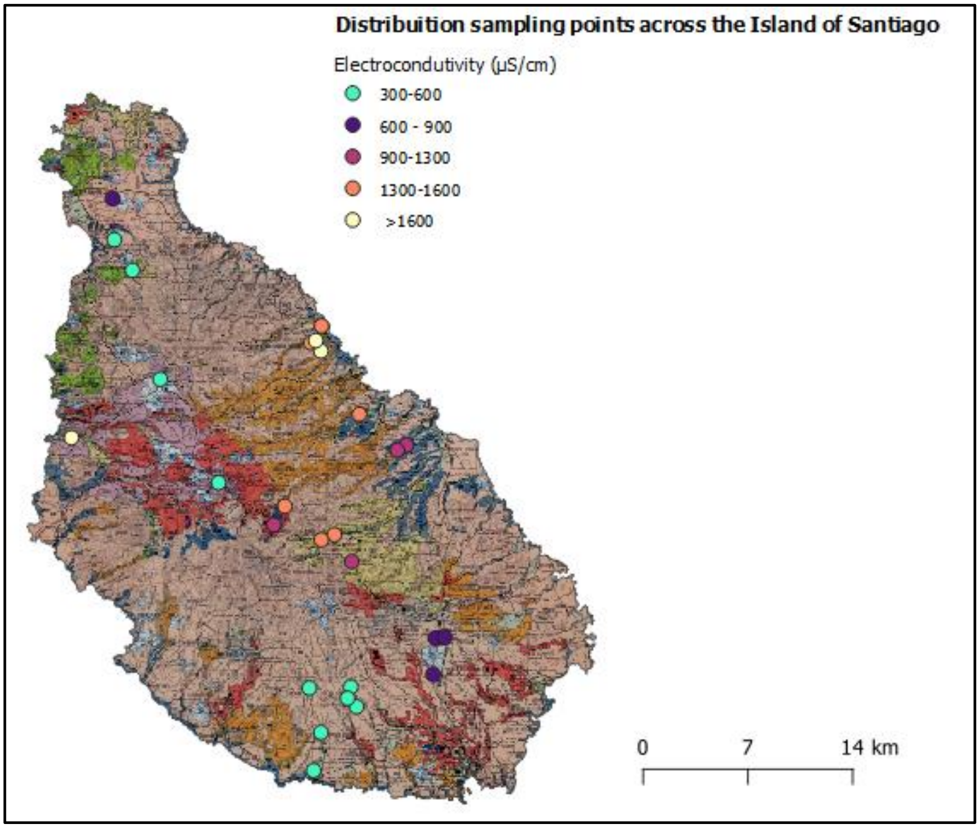


Figure 7 - Distribution map covering different type of lithological formations on island of Santiago showing the EC measured values. Accuracy ±1 % full scale

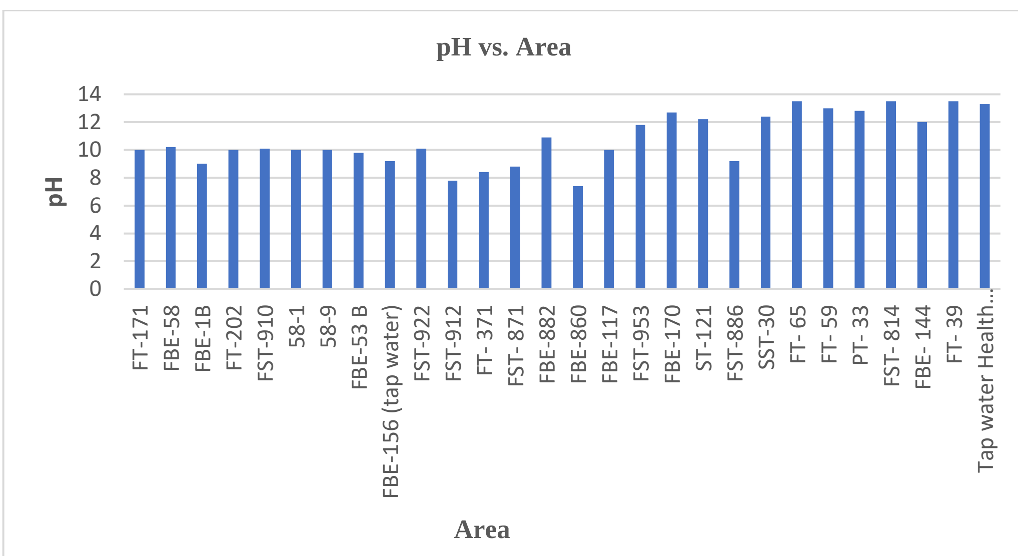


Figure 8- pH values for each sampled point (these are absolute value) across the municipalities.

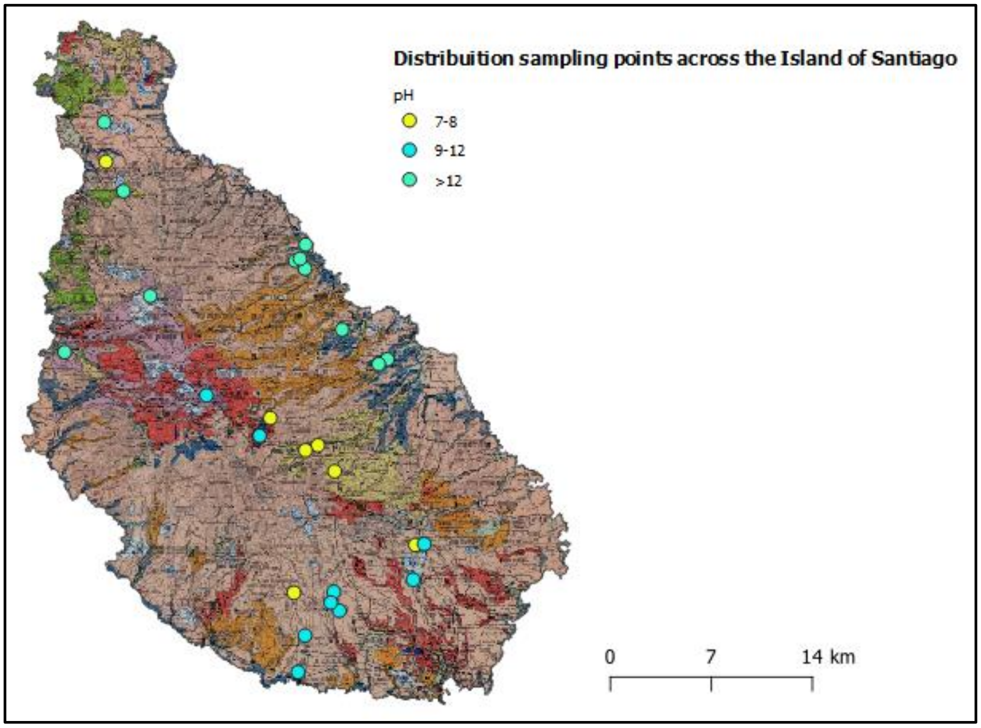


Figure 9- Distribution map covering different type of lithological formations on island of Santiago. It was performed using PCTestr 35 a waterproof multiparameter testers with accuracy of ±0.1 for pH.

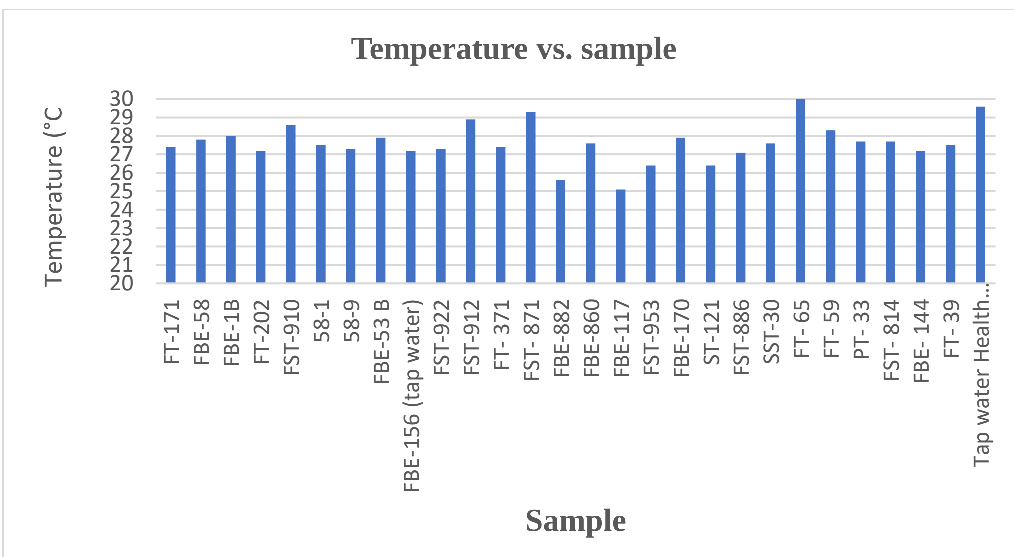


Figure 10 – Water samples temperature values at the time of sampling for each sampled point (these are absolute value) across the municipalities. Accuracy ±*0,5*

Those physical parameters were included in order to give the basic profile of the subsurface water on the different aquifers and locations. Even though this study does not have duplicate samples to show different water characteristic during dry and wet period in order to provide an accurate data, it still can show the variability of the nature of the water across the island. The electroconductivity is an important parameter which measures how much dissolved salts are in the water, it varies on a scale from 0 to 50,000 µS/cm. According to the water quality regulation in Cape Verde the maximum parametric value (VP in Portuguese) is 2000 µS/cm for EC. The conductivity reference temperature is 25 °C for the standard calibration used during the sampling.

The pH shows the hydrogen ion concentration on a solution and the limit for the drinking water for human consumption in Cape Verde are 6.5 to 9.5 on the Sorensen scale and the temperature 25^{0}C. All sampled water was destinated for drinking consumption and these are absolute value.

The *in situ* measurement results showed high salinization across the island especially on the coastline (SMG, STC), and on agricultural zones in the valleys by the seaside surroundings. This salt increase may be interconnected with intense exploitation of the hydrological resources and the scarcity of precipitation. The EC value varying from 375 µS/cm to the highest absolute value of 1775 µS/cm found at Sao Miguel (FT-39) a coastal zone, and the second highest value at Ribeira da Barca (FBE-170) on the valleys near to the sea. In those area, during a conversation with the community they state that the water is becoming brackish each day.

The average EC is 929.64 µS/cm, pH is 10.77 and the average temperature is 27.66 ^{0}C. The highest value found of EC by other study is up to 9400 µS/cm, located in the valleys, areas of intense agriculture practice such sugar cane, banana, papaya fields (Carreira *et al*., 2010). Those high values could be explained due to natural environmental features such as mineral springs, carbonate deposits, salt deposits, and sea water intrusion.

The study about sustainable and environmental hydrology, hydrogeology, hydrochemistry and water resources (Carreira *et.al*, 2019) corroborate that the groundwater with the highest salt content are found near the coastline, mostly in valleys known for being the busiest agricultural area on the island, with excessive pumping of the aquifer systems, revealing the effect of saltwater intrusion. The water is characterized by meteoric water derived from run of precipitation with rapid infiltration.

(Carreira *et al.*, 2019) on geochemical and isotopic marks for tracing groundwater salinization at Island of Santiago shows that the mean temperature of the groundwater samples is approximately 25.4 ^{0}C and the Electroconductivity varies between 130 to 10,000 µS/cm. Their isotopic composition of the water suggested that all groundwater is meteoric water and most of them are not subject to the previous evaporation before recharge.

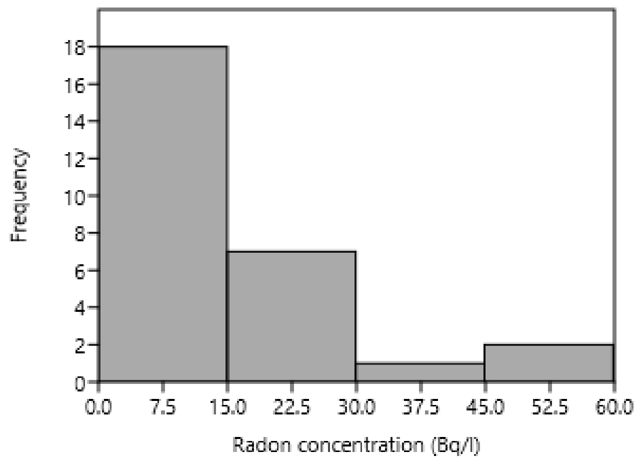
It is important to emphasize that in Santiago there is different hydrographic basin with those value varies according to the soil type, agriculture and others activities practiced on the area, aquifer type ex: how much is time of aquifer recharge.

According to many studies at Santiago there is a tendency for increasing water salinity and the intensification of use of brackish water in agricultural field due to the scarcity of precipitation. Thus, the deterioration of the water quality limits its use for human leading to a potential outlet for soil salinization and alkalinisation, with the inherent soil deterioration and loss of productivity. According to (Pina, *et al*., 2005; Santos *et al*., 2010) the amount of water supplied for irrigation usually exceeds the drainage capacity of the soil. So, brackish groundwater for agriculture and human at the coastal areas, is provided to many parts of the island as the only type of available water.

5.2. Results for radon measurement

The Activity concentrations in (Bq/L) as well as the uncertainty for the twenty-nine (29) water samples calculated are listed in table 2 on the Appendice.

Below are the graphics and maps showing the main results.



Statistical Indicator	[^{222}Rn] (Bq/l)
N	28
Min	0
Max	59.85
Sum	414.04
Mean	14.78714
Std. error	3.031115
Variance	257.2544
Stand. dev	16.03915
Median	9.43

Figure 11 - Histogram and boxplot of sampled water points data about radon concentration measurement across the island.

The graphics shows the number of times a result occurs for radon concentration measurement (n= 29). As it can be seen the samples have different level of radon concentration ranging from 0 Bq/L to 59.85 Bq/L. The distribution has a mean of 14.78 Bq/L, Standard error of 3.03 Bq/l, the variance of 257.25 Bq/l, the standard deviation of 16.03 Bq/L and the median of 9.43 Bq/L. The box plot shows that the majority of data presents low level of radon concentration. The test for normality was performed using Anderson – Darling which the P value shows having a distribution significantly different from the normal, with p (normal)= 0.00028. This test was chosen for univariate sample and this theoretical distribution is widely used for geostatistical study of the spatial distribution of minerals and formation of soils (Alonso *et al*., 2019). For this reason, Kruskal-Wallis test was used as nonparametric test and the p value did not reject the hypothesis of this study, that radon concentration is not homogenous across the island and there can be an association between radon concentration, rock types and physical properties of the environment (p= 0.1268> 0.05).

In the figure 12, shows 4 categories of geology which was studied across the island, which it can be seen the radon concentration accordingly to each category.

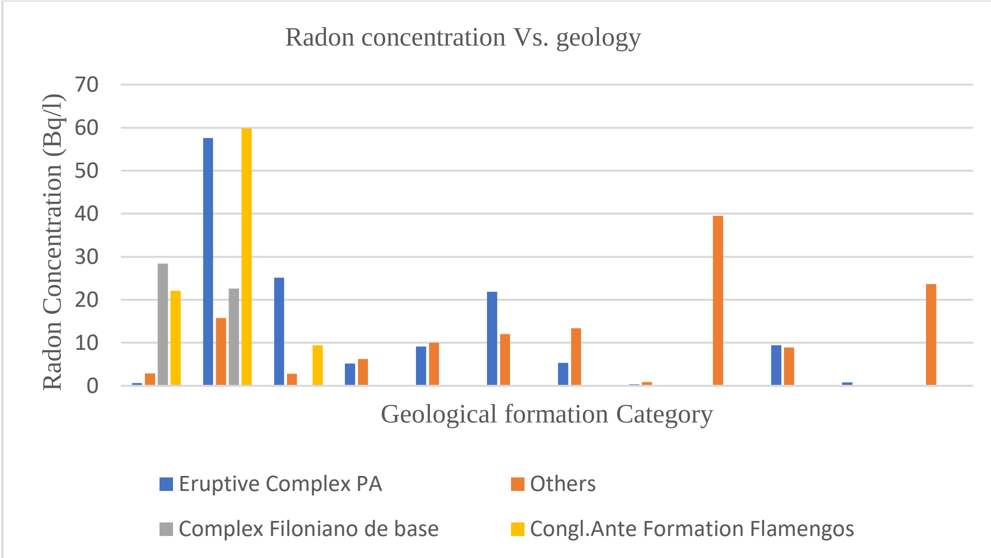


Figure 12 - Graphics shows the radon activity per category of type of geology, where Complex Filoniano de base and Conglomerates Ante Formation Flamengos have less representativity

These categories were created in order to see the spatial distribution of radon concentration in each formation. The Statistical analysis suggests that the samples from the 4 categories, out of which two has more data (11 or 12), while the other two much less data (2 or 3). The Eruptive Complex PA and Others type of rocks including chimney, pyroclast, dykes' components are very similar (means), while the other two sites are much more different (Table 3 on the Appendice). It's a constraint that there is insufficient data for conglomerate ante formation Flamengos and Complex Filoniano de base indicating the values are more spread out and less reliable from the mean. For this reason, Mann- Whitney U test was performed between the two categories with more data (Eruptive Complex PA and Others type of rocks) to see if there is no significant difference of radon concentration on these types of geology. Since the p value 0.5795 is bigger than 0.05, thus there is no difference in radon concentration according to the two category considered. The average of radon concentration on the Eruptive Complex PA and Others are 12.32 Bq/L and 11.34 Bq/L and variance 17.29 and 11.22 respectively.

The reason of the different concentration found at side by side at two same localities or same geology formation can have many factors, for example, well depth, the structure of the well, or other environmental factor such as the characteristic of those aquifer system.

The Correlation between Eletroconddutivity and radon concentration measured were done in order to see the linear relantioship between the two variables (**Fig. 13**). It shows that there is no linear relantionship between them, the R^2 value of the linear regression is 0.0289 which means that only 2.9 % of the variation of data is due to change in EC and the remaining 97.1% is attributed to random factors. It may have others environmental factors that might contribute to the presence of radon in the samples studied. According to (Smith and Kennedy, 1983 *apud* Somogyi & Lénárt, 1986) the radon solubility may vary with waters containing mineral salts, as radon solubility is higher in pure water, that others waters with influence of salts.

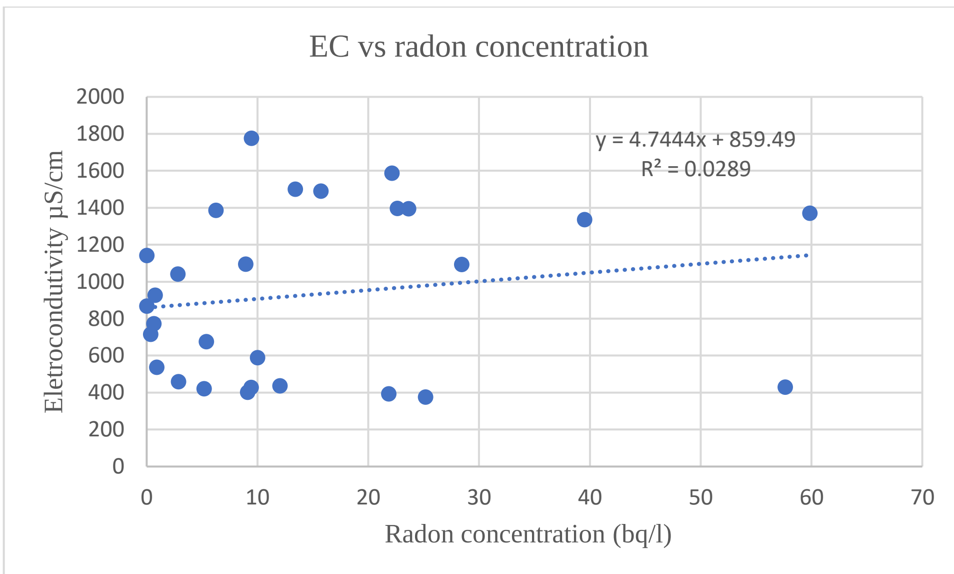


Figure 13 - The figure shows the correlation between EC and Measured radon concentration on the sampling points

The Table 6 shows the comparison of the five highest value of radon concentration in relation with others parameters such as radon concentration, EC for a specific code area giving details about the geologic description.

Table 6

Comparison of the five highest value of radon concentration with others variables

[^{222}Rn] (Bq/l)	EC (µS/cm)	Area	Geology	Description
59.85	1371	SMG - FBE 144	Conglomerate ante formation Flamengo	Overlaps with Ancient Internal Eruptive Complex (CA)
57.62	429	CV -FBE 58	Eruptive Complex Pico de Antonia (PA)	Basanitic lava flows intermittent pyroclasts material, domes, dyke, phonolitic trachytic
39.52	1335	STC- FT 65	Dykes, Chimneys pyroclasts – Ancient Internal Eruptive Complex (CA)	Dense dykes complex, alkaline syenite rocks, intravolcanic breccias, phonolites, trachyte carbonatites, pyroxenites
28.44	1093	SSM - FBE 882	Foloniano Complex Base	Basaltic nature, limburgites, basanites, ankaratrites
25.16	375	*CV - FBE 1B	Eruptive Complex Pico de Antonia (PA)	(phonolitic trachyte, basaltic, dykes chimney pyroclasts)

Note: Representation of five highest radon concentration in comparison with Area, geologic formation and its Electroconductivity value. The geological formations include the main formations and the lithology unit. Those are sample water from well and * represents the sampled water from a drink fountain pipe (Bedouro de Achada at Salineiro belong to Cidade Velha municipalities).

The highest value found is 59.85 Bq/l ± 9.5 at Sao Salvador do Mundo at Conglomerates ante formation Flamengo which the characteristic overlaps with Ancient Internal Eruptive Complex (CA) and those are found on the well points. The water sampled from the spring did not show as the highest (58-1 = 2.88 Bq/L and 58-9 = 21.84 Bq/L) as we are expecting. The uncertainty shows high due to the time delay between sampling and measurement (See appendices). As it can be seen the values for each parameter it's not homogenous across the island, wherein the radon concentration was found in almost all type of lithology formation. The PA formation is the largest representation on the island represented basically by phonolitic – trachyte and basaltic rocks. According, to study carried about uranium contents in the lithological formations of Santiago Island states that the island is constituted by basaltic- basanite rocks, and highlighted that phonolitic- trachytic rocks also occur. It showed that the highest content of uranium occurs in the phonolitic- trachytic rocks of Ancient Complex and Pico Antonia Formations, and also in the other formations of heterogeneous materials, which have phonolitic- trachytic fragments, reaching 62.8 µg/g of uranium. This value is 30 times higher than the world average in soil, where it should be found higher radon concentration at Santiago. The source of uranium in the rocks of Santiago is related with the occurrence of zircon (Pinto *et al*., 2014). It might lead to not reject the hypothesis that the radon concentration is not homogenous across the island and there can be an association between rock type and physical properties of the environment.

Figure 14 and 15 shows the distribution map of radon concentration on subsurface water samples across the island of Santiago using measured data computed on QGIS software.

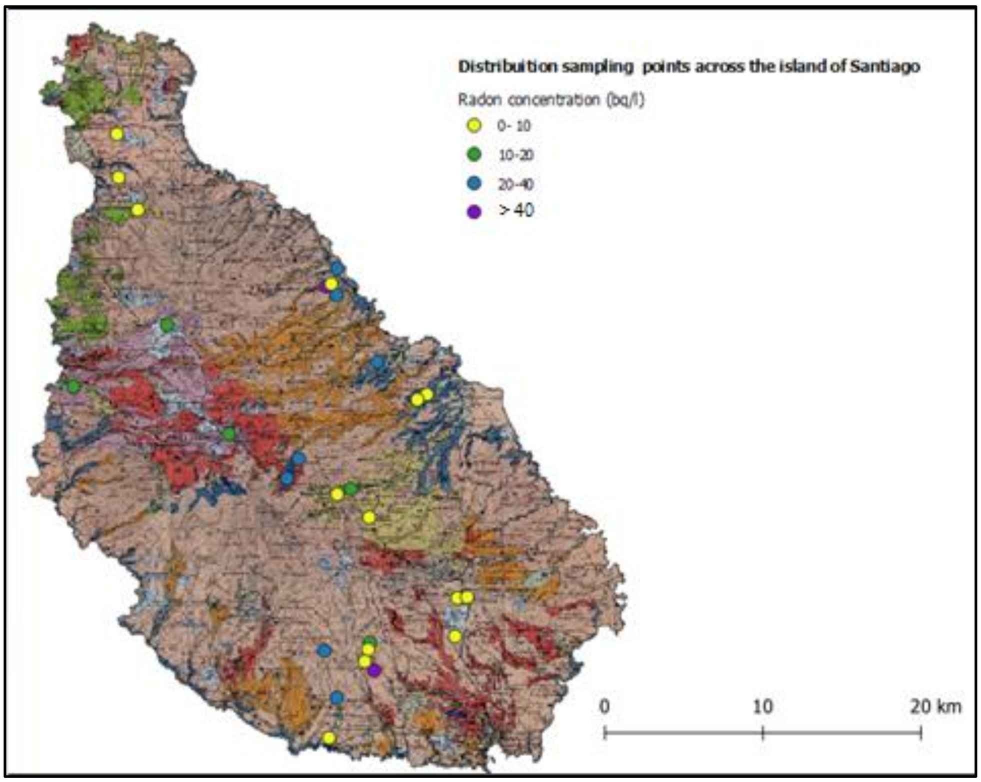


Figure 14- Sampling points displaying radon concentration, the graphic shows the points sampled according to the geology of the place. The description was based on geologic map by Serralheiro 1974 in Pereira 2010. Radon concentration vs. geology.

Table 7

Comparison of the average of radon concentration by municipalities/ sampled area

Municipality	PR	RGS (CV)	SD	SLO	SSM	STC	TAR	SC	SMG
[222Rn] Bq/l	0.65	20.3	1.91	8.25	**25.53**	11.81	3.69	16.14	**28.76**

The higher value of the average of radon concentration per cities appear on SMG – Conglomerates ante formation Flamengos and SSM – Complex Filoniano de Base. Since those area have fewer sample points representativity for the future studies it can be consider for further analysis.

The tap water concentration showed lower concentration than the spring and well water sampled as 0.36 Bq/l (SD) and 23.64 at (SMG).

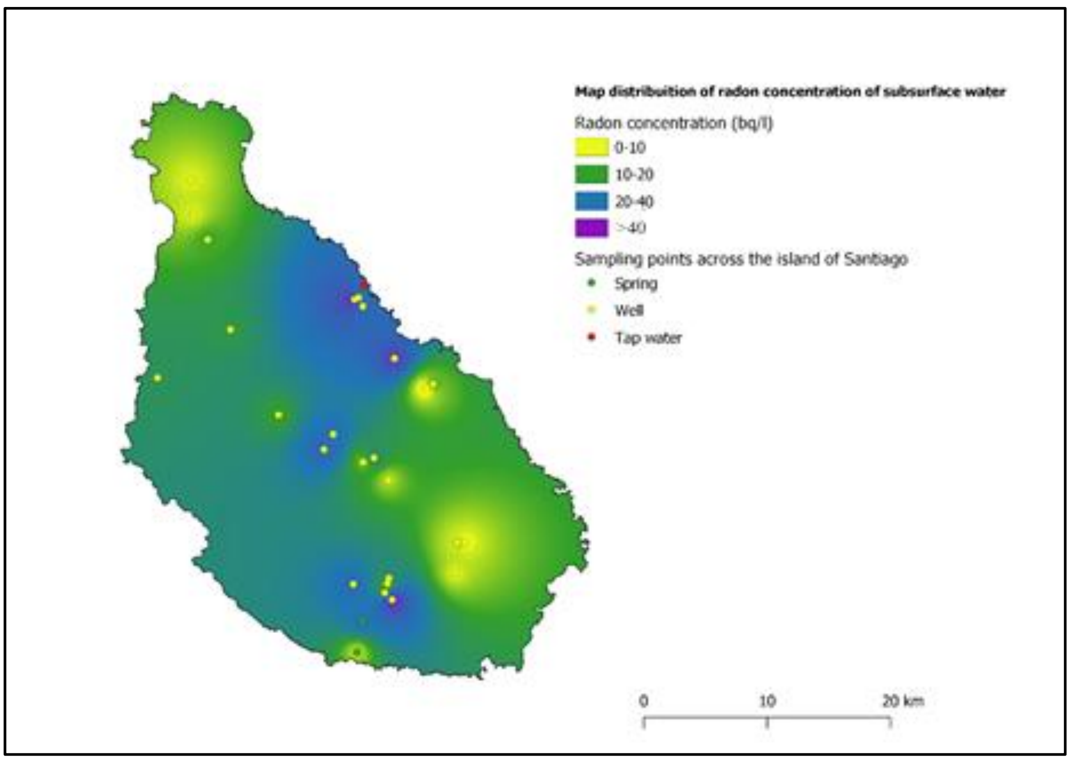


Figure 15 - Distribution map displaying the radon concentration across the island. Inverse Distance weighting interpolation was applied (Own work).

The basic principle of IDW is that points are weighted such that the influence of one point relative to another is a function of inverse distance. Weighting is assigned to points through the use of a weighting power (p= 2 used by default).

The produced maps can be used as a first step in identifying areas of possible radon inert gas for any future investigations and remedial actions.

6. CONCLUSION

Radon 222 has been analysed *ex situ* in subsurface water across the island of Santiago, using the LSA technique by Tricarb 1000 device at ELTE radon laboratory, whereas Electrical conductivity, hydrogen ion concentration and temperature (ºC) were measured *in situ*.

Radon concentration in the water samples studied varies between 0.2 Bq/L and 59.8 Bq/L.

There is no regulation for radiological protection limit for radon gas concentration at Cape Verde, but on Macaronesia region the limit of 222Rn in drinking water is 100 Bq/L, therefore the values obtained for all analyzed samples are bellow this threshold.

There is a substantial variation in radon concentration across the island but it does not seem to follow a definite spatial pattern for a specific type of rocks, since very different concentrations were detected side by side at two same localities, rock type thus, there is no close association between radon concentration with a specific rock type or water EC in our data.

There is a need for further investigations on those area/ geological formation that showed higher radon concentration at Santiago Island, furthermore natural radiation in the geological formations in others islands especially Fogo and Brava for their rock characteristics. The study that investigated uranium contents in the lithological formations of Santiago Island (Pinto et al., 2014) states that he highest content of uranium occur in the phonolitic- trachytic rocks of Ancient Complex and Pico Antonia Formations, and also in the other formations of heterogeneous materials, which have phonolitic- trachytic fragments, and since the largest formation is represented by PA, it might explain the heterogenous valued found of radon222 across the island.

Since this is a preliminary study, which does not lead to strong conclusions, yet the results may be appropriate to initiate further in-depth studies with more samples points using two campaigns at different period of time (dry season and wet season) and different radon measurement techniques like in situ measurement to reduce the uncertainties. For this study the uncertainty seems higher due to the time delay between sampling and measurement (average ± 5.9). There is a need for building a database of georeferenced radiological information that comprises radon concentration in order to monitor the evolution.

Summary

Radon-222 in drinking water becomes pertinent all around the world because of its health issues and its mobility on soil, air and water systems. This research measures the radon concentration of subsurface water for human consumption from well and spring, covering all lithological formations across the Island of Santiago. The geology of the Island makes this study important due to the public water sources, used for service and drinking purposes, which are primarily from springs and wells and because of the variability in geological formations. The total sampling point is 29, at which the pH, EC and T where measured in situ, and the analytical measurement for radon activity were carried out at ELTE university – Hungary. All the sampling work procedure last 3 days and after two days the water samples were transported to Hungary. The method applied for radon measurement was Liquid Scintillation Analyser (LSA) using tri carb 1000 device, which is considered one of the most important analytical method for this kind of analyses. The geological background was studied in order to understand the correlation and the possible origin of radon, since the island is from volcanic origin constituted of basaltic, phonolitic – trachytic rocks, which consist the largest development on the island. The main goal of this study is to explore the spatial heterogeneity of radon concentration distribution across the island and to try to find relationships with environmental factors awareness for future monitoring system, thus the study of radon inert gas performed will help to assess if the obtained data can be used to establish the local controls are needed.

The results showed that there is a lower level radon concentration across the island and according to non-parametric test applied it seems that there is no spatial pattern on radon concentration according to the rock types/ geology formation. This preliminary study allowed to have data to further explore the radon gas on subsurface water at Cabo Verde extending to others islands. The results of T, EC and pH are absolute values, and one sample point measurement which showed that there is no linear relationship between radon concentration and EC.

Acknowledgment

To God for his mercy and opportunity to be alive;

To my advisor Dr. Akos Horvath, which always found a moment to work with me at the laboratory, and embraced the thesis topic for the very first moment, he truly supported the idea to explore radon on subsurface water at Cabo Verde;

To my professor Tibor Kalapos for being patient and kind helping me with statistical analysis and all support;

To all the people who participated in this work, especially to Adelcides Varela supporting me with QGIS software, Professor Balazs Szekely with his advices, Dilma Landim for facilitating me the datas, all technicians at ANAS (National Agency for Water and Sanitation);

To the Mr. Antonio Pedro Pina Adminstrator of ANAS to authorize Mr. Ricardo - Djica who accompanied me throughout the sampling process and for his knowledge transmitted;

To my professor Antonio Lobo de Pina, for always being available, via Skype providing me useful information about geological formations on Santiago Island;

To the National Agency for Water and Sanitation, Dr. Antonio Pedro de Pina and my CEO Olivio Ribeiro, which was always available to collaborate in order to accomplished my fieldwork in a short period of time;

To all Technicians who willingly accepted to collaborate with me in the field work during the collection of water sample in each stations and all agency supervisors that took the time to guide me in each municipalities, especially Enio Fontes at Sao Minguel, Mr. Landim at Tarrafal, Zuca at Assomada;

To my friend (Filu), who unconditionally dedicated efforts to carry out and supported me during the collections and writting;

For the Hungarian Government for the Sholarship throught the Tempus Public Foundation and ELTE University for giving me the oppotunity to learn Science and for having welcomed me as a potential candidate believing on me until the end;

To the physics and geology department of ELTE that provided equipament for the collection and analysis;

To all my teachers who contributed in some way to my academic training, and to all who cooperated to finish this stage, especially, Elizabeth Toth, I will never forget that hug and chocolate you gave me when i was passing through hard time;

To my professor Tamas Weiszburg,who taught me tireless;

To Nagy Eva, Zsuzsanna Hannus which truly represented my second family here;

Definitely, I will be a better professional and person after this experience I had at ELTE community;

To all my classmates and my roommates, especially Roja Medianista for emotional support; To my mother Maria Sequeira for her courage and good example;

To my sister Evily Martins for her emotional support; To my brother Admilson Barbosa for his patience and friendship; To my two nieces, for the videos and the joy transmitted.

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PANA-II - Plano de Acão Nacional para o Ambiente II

PEDS – Plano Estratégico de Desenvolvimento Sustentável

INDC - Intended nationally determined contributions

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Advanced Lan Observing Satellite retrieved from
https://www.eorc.jaxa.jp/ALOS/en/aw3d30/index.htm retrieve at 05/04/2020

APPENDICE

Table 1

The sample locations and its geographical references

Code	**Localities**	Latitude	Longitude	Coordinate X	Coordinate Y
FT-171	PR	14.97996	-23.52967	212178	34146
FBE-58	CV	14.95994	-23.57719	207070	31920
FBE-1B	CV	14.97153	-23.60648	203916	33197
FT-202	CV	14.97214	-23.5808	206679	33270
FST-910	CV	14.96516	-23.58279	206466	32497
58-1	CV	14.92037	-23.60381	204215	27536
58-9	CV	14.94396	-23.5993	204695	30147
FBE-53 B	SD	15.00238	-23.52705	212453	36628
FBE-156	SD	15.00241	-23.52826	212323	36631
FST-922	SD	15.00296	-23.52253	212939	36693
FST-912	SLO	15.0666	-23.59099	205563	43719
FT- 371	SLO	15.04985	-23.58018	206729	41868
FST- 871	SLO	15.06341	-23.59902	204700	43365
FBE-882	SSM	15.07276	-23.62857	201521	44393
FBE-860	SSM	15.08425	-23.62167	202261	45666
FBE-117	ASS	15.09885	-23.6628	197836	47274
FST-953	FUN	15.16299	-23.69903	193931	54365
FBE-170	RBA	15.12674	-23.75411	188017	50346
ST-121	TAR	15.23052	-23.71625	192071	61834
FST-886	TAR	15.24952	-23.72752	190857	63934
SST-30	TAR	15.27501	-23.72858	190739	66755
FT- 65	STC	15.14125	-23.57544	207218	51982
FT- 59	STC	15.12206	-23.5463	210354	49866
PT- 33	STC	15.11897	-23.55189	209754	49522
FST- 814	SMG	15.18049	-23.5993	204645	56319
FBE- 144	SMG	15.18562	-23.60556	203972	56888
FT- 39	SMG	15.18695	-23.60249	204301	57033
Tap water	SMG	15.19606	-23.5989	204685	58041

Note: The table shows the location with new codes for the wells and the spring (ANAS,2020), displaying the coordinates for each sample water points. (* represent Spring). Source: (ANAS adapted ,2020).

Table *2*

Activity concentrations in (Bq/l) and uncertain

sample	sampling				calibration		calibration cpma		11.29	1.98		
name	month	day	hours	min	bck	slope	Delta T	decay loss	c(meas) Bq/l	c(origin)	unc	unc%
SALFBE1B	8	28	9	12	10.18	1.98	250.8568	0.1503376	3.782828283	25.16223172	4.621552	18.37%
SSMFBE882	8	28	13	52	10.18	1.98	252.0688	0.1489675	4.237373737	28.44495497	4.805992	16.90%
SSMFBE860	8	28	14	33	11.29	1.98	274.5867	0.1256672	2.843434343	22.62669588	5.172138	22.86%
PRFT171	8	28	11	22	11.29	1.98	275.64	0.1246713	0.080808081	0.648168877	4.090745	631.12%
SDFBE53B	8	28	11	47	11.29	1.98	287.7883	0.1137402	0.611111111	5.372865987	4.727712	87.99%
FT202	8	28	10	30	11.29	1.98	288.81	0.1128659	0.585858586	5.19075094	4.755312	91.61%
SDHFBE156	8	28	12	25	11.29	1.98	289.8283	0.112001	0.04040404	0.360747075	4.535767	1257.33%
SDFST922	8	28	11	35	10.18	1.98	290.845	0.1111442	-0.282828283	-2.544696659	4.412771	-173.41%
CVG58-1	8	28	8	15	10.18	1.98	291.8633	0.1102926	0.318181818	2.884889421	4.738739	164.26%
CVmix	8	28	11	15	11.29	1.98	292.88	0.1094488	1.898989899	17.35048536	5.515786	31.79%
CVFST910	8	28	10	47	11.29	1.98	295.9967	0.1069022	0.974747475	9.118119426	5.206722	57.10%
CVFBE58	8	28	10	12	11.29	1.98	298.0283	0.1052742	6.065656566	57.61768835	7.595789	13.18%
CVG58-9	8	28	8	39	11.29	1.98	315.4617	0.0922852	2.015151515	21.83612332	6.596945	30.21%
TRSST30	8	30	17	5	11.29	1.98	316.48	0.0915781	0.070707071	0.772096009	5.564964	720.76%
TRFST886	8	30	16	40	11.29	1.98	317.4983	0.0908764	0.080808081	0.889209069	5.612006	631.12%
TRSST121	8	30	16	9	11.29	1.98	318.5183	0.0901789	0.848484848	9.408909235	6.101472	64.85%
SCFST953	8	30	13	20	10.18	1.98	319.5367	0.0894879	1.075757576	12.02126663	6.279869	52.24%
SCFBE117	8	30	13	57	10.18	1.98	320.5567	0.088801	0.888888889	10.00989198	6.220907	62.15%
RBFBE170	8	30	11	46	11.29	1.98	321.5783	0.0881184	1.181818182	13.4117097	6.435146	47.98%
SLOFST871	8	28	16	16	11.29	1.98	322.6	0.087441	0.545454545	6.237974663	6.111637	97.97%
SLOFST912	8	28	13	5	11.29	1.98	334.4333	0.0799642	1.257575758	15.72672497	7.138128	45.39%
SLOFTE371	8	28	12	47	11.29	1.98	335.46	0.0793465	0.222222222	2.800654834	6.522922	232.91%
SCUFT59	9	2	10	46	11.29	1.98	336.4817	0.0787365	0.702020202	8.916066017	6.890876	77.29%
SCUPT33	9	2	10	55	10.18	1.98	337.5283	0.0781165	-0.363636364	-4.655052119	6.222967	-133.68%
SCUFT65	9	2	13	5	11.29	1.98	338.6883	0.077435	3.060606061	39.52483269	8.527354	21.57%
SMFBE144	9	2	14	16	11.29	1.98	340.6667	0.0762865	4.565656566	59.84884078	9.589586	16.02%
SMFT39	9	2	14	30	11.29	1.98	341.6817	0.0757038	0.712121212	9.406674561	7.178095	76.31%
SMFST814	9	2	14	5	11.29	1.98	342.7067	0.07512	1.661616162	22.11950498	7.872797	35.59%
SMTWH	9	2	15	0	10.18	1.98	343.7	0.0745584	1.762626263	23.64087514	3.859762	16.33%

Note. The measurement of the Activity concentrations in (Bq/l) as well as the uncertainty. The full excel sheet are available on the zip document. The background chosen and the slope are 11.29 and 1.98 respectively according to the calibration method described

Table 3

Average and standard deviation of water radon concentration by geological formations

	Eruptive Complex PA		Others		Complex Filoniano de base		Congl.Ante Formation Flamengos	
	[222Rn]	EC	[222Rn]	EC	[222Rn]	EC	[222Rn]	EC
	0.65	773	2.88	458	28.44	1093	22.12	1586
	57.62	429	15.73	1490	22.63	1397	59.85	1371
	25.16	375	2.8	1041			9.45	1775
	5.19	421	6.24	1386				
	9.12	401	10.01	589				
	21.84	393	12.02	436				
	5.37	676	13.41	1500				
	0.36	716	0.89	536				
	0	868	39.52	1335				
	9.41	427	8.92	1095				
	0.77	926	0	1142				
			23.64	1395				
Avearge	12.32		11.34		25.54		30.47	
SD	17.29		11.22		4.11		26.22	

Table 4

Sampling Report made available from ELTE Dept. Atomic Physics, Tricarb 1000 TR for Radon-in-water measurement

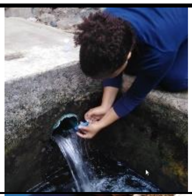
Name of the series: Cape Verde 1   date: 2019. aug 28. – sep 2.

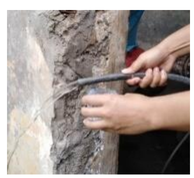
Sampled by: Helen Deise Sequeira Barbosa

Sampling area: Santiago Island, Cape Verde

Sample code	Sampling site	Site picture	Sampling type*, details	Sampling time	koncent-ráció Bq/l	koncent-ráció hibája (Bq/l)
SALFBE1B	Bebedouro de Achada Salineiro : 2 distribuition pipe Salineiro and Praia		A: 2	09:12	25.162232	4.621552
SSMFBE882	Sao Salvador do Mundo		A:2	13:52	28.44495497	4.805992
SSMFBE860	Sao Salvador do Mundo		A:2 from a ventoso to syringe	14:33	22.62669588	5.172138

PRFT171	Praia		A:2 from a resevoir tap, which the water comes directly from a well	11:22	0.648168877	4.090745
SDFBE53B	Sao Domingos		A:2 On a syringe from a ventoso Pumping machine	11:47	5.372865987	4.727712
FT202	Joao Varela (CV)		A:2 On a syringe from a ventoso Pumping machine	10:30	5.19075094	4.755312
SDHFBE156	Sao Domingos		C:2 From a tap water, that comes directly from well FBE 156. Is the first house conected	12:25	0.360747075	4.535767
SDFST922	Sao Domingos		C:1	11:35	- 2.544696659	4.412771

CVG58-1	Convento – Cidade velha		A:2	08:15	2.884889421	4.738739
CVmix	Cidade Velha Resevoir (202) with the water mixture from well 58 and FBE1- B		B:3	11:15	17.35048536	5.515786
CVFST910	Cidade Velha		A:2	10:47	9.118119426	5.206722
CVFBE58	Cidade Velha		A:2	10:12	57.61768835	7.595789
CVG58-9	Cidade Velha on Galery water		A:2	08:39	21.83612332	6.596945
TRSST30			A:2	17:02	0.772096009	5.564964

TRFST886	Tarrafal		C:2 from a resevoir pipeline which the water come from direct from well	16:40	0.889209069	5.612006
TRSST121	Tarrafal		A:2 from a pumbing house machine trough ventosa	16:09	9.408909235	6.101472
SCFST953	Assomada - fundura		A:2 In a pumbing house machine from a ventosa.	13:20	12.02126663	6.279869
SCFBE117	Assomada - Bolanha		A:2 In a pumbing house machine from a ventosa.	13:57	10.00989198	6.220907
RBFBE170	Ribeira da barca It supply all village		A:2 From a pipe directed conected to the well in a pumpinghouse machine. Really near to the coast sea	11:46	13.4117097	6.435146

SLOFST871	Sao Lourenco dos Orgaos		A:2 From a pipeline directed connected to the well, which is pumped out.	16:16	6.237974663	6.111637
SLOFST912	Sao Lourenco dos Orgaos		A:2 From a tap, directed connected to the pumphouse machine	13:05	15.72672497	7.138128
SLOFTE371	Sao Lourenco dos Orgaos		A:2	12:47	2.800654834	6.522922
SCUFT59	Santa Cruz		A:2	10:46	8.916066017	6.890876
SCUPT33	Santa Cruz		A:2	10:55	- 4.655052119	6.222967

SCUFT65	Santa Cruz		A:2 Overexplored and near to sea coastal	10:02	39.52483269	8.527354
SMFBE144	Sao miguel		A:2 From a pumpingmachine to with syringe to Vials	14:16	59.84884078	9.589586
SMFT39	Sao miguel			14:30	9.406674561	7.178095
SMFST814	Sao miguel		A:2 From a pumpingmachine to with syringe to Vials	14:05	22.11950498	7.872797
SMTWH	Sao Miguel	N. A	A:2 From a a tapwater in a public health delegacy	15:00	23.64087514	3.859762

A: on site to a vial,	1: with syringe, from open surface water,
B: on site to a bottle,	2: with syringe, from a pipe (outflowing time should be noted),
C: anything else	3: with bailer to a syrindge,
	4: syringe only in the lab.

The details of the sampling procedure should be noted in 3. column
Comments and remarks, name of the excel file:

STATEMENT

Name: Helen Deise Sequeira Barbosa
Neptun ID: QNZ55R
ELTE Faculty of Science: MSc Environmental science
specialization: Applied Ecology
Title of diploma work: Assessment of subsurface water in Island of Santiago - Cabo Verde, with emphasis in spatial distribuition of radon concentration

As the author of the diploma work I declare, with disciplinary responsibility that my thesis is my own intellectual product and the result of my own work. Furthermore I declare that I have consistently applied the standard rules of references and citations.

I acknowledge that the following cases are considered plagiarism:
– using a literal quotation without quotation mark and adding citation;
– referencing content without citing the source;
– representing another person's published thoughts as my own thoughts.

Furthermore, I declare that the printed and electronical versions of the submitted diploma work are textually and contextually identical.

Budapest, 2020

Helen Barbosa
Signature of Student