How do CO_2 and radon gases affect groundwater mining in the Canary Islands?

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Abstract

Water galleries are mines that seek to supply drinkable and irrigation water from the aquifer, in order to meet the demand for water in the Canary Islands. This sort of work entails a series of health risks in the form of gases. This document compiles three different studies on the gases that can be found in water galleries in the Canary Islands, having divided the document as follows: 1) the presence of carbon dioxide in 13 galleries in operation on the island of Tenerife; 2) the presence of radon gas in galleries on the islands of Tenerife, El Hierro and La Palma; and 3) the incidence of gases that are harmful to health in a thermal water gallery on La Palma. The results have shown that, in general, the water galleries contain concentrations of gases which are toxic to human health, such as radon, where average radon values measured with both passive detectors are from less than 800 Bq/m^3 to around 10,200 Bq/m^3. Therefore, it is important to protect the health of the workers who undertake the maintenance of these installations.

keywords: water galleries; safety; carbon dioxide; radon.

1. Introduction

The extraction of groundwater in the Canary Islands has been an important source of water in the archipelago, especially in quantitative and qualitative terms (Santamarta, 2016). Mainly, the extraction of groundwater has been done through galleries and wells (Coello-Bravo *et al*., 2020). The galleries are mining excavations that are sensibly horizontal, drilling geological formations until reaching the water-saturated zone, from where water is extracted by gravity, thanks to the fact that they are built with a slight slope (Santamarta *et al*., 2020).

The problem generated by the presence of gases in the galleries of Tenerife is a consequence of two phenomena: an increase in the concentration of carbon dioxide or a decrease in the concentration of oxygen by processes that consume this gas or by displacement due to the increase of CO_2 (Marrero *et al*., 2008). The atmosphere of the galleries located in areas of gas emission is characterized by the absence of a heterogeneous composition (Padrón *et al*., 2013), as well as by a remarkable temporal variability, mainly due to the following aspects: a) nature and characteristics of the materials crossed; b) presence of water; c) existence of ventilation devices and d) seasonal and daily variation of the balance between atmospheric conditions outside and inside the galleries.

In addition, it is also considered necessary to carry out measurements of radon levels in the galleries, since radon gas is associated with lung cancer, as stated by the World Health Organization (WHO). Radon is a natural radioactive gas that can cause health problems at work, especially in volcanic territories such as the Canary Islands (Eff-Darwich *et al*., 2008). Radon (Rn^{222}) is a natural radioactive noble gas from the uranium-238 disintegration chain and therefore is ubiquitous in nature (Padilla *et al*., 2013). This gas presents low levels in the open air but tends to accumulate in houses and buildings, which can lead to high concentrations, especially in areas with permeable soils or those with a high Ra content (Khan *et al*., 2012; Verma *et al*., 2012). The release of radon from the soil to the atmosphere involves three processes: emanation, transport and exhalation, in which radon atoms transported to the ground surface exhale into the atmosphere (Thu *et al*., 2019). According to the WHO, above a radon gas concentration of 100 Bq/m^3, the probability of lung cancer increases considerably. Areas with values above 300 Bq/m^3 should not be considered habitable (Santamarta *et al*., 2021).

Also, thermal waters in volcanic territories may contain gases of volcanic origin that, depending on their concentration, can be hazardous to health. The main gases that can be found in thermal waters are hydrogen sulphide, noble gases, hydrocarbons, etc. (Carvalho *et al*., 2011) and carbon dioxide (Safarov *et al*., 2012). In fact, one of the gases that escapes earlier to the natural environment is CO_2, due to its low solubility (Marrero *et al*., 2008).

The area of this study is the archipelago of the Canary Islands, an outermost European region belonging to Spain. The westernmost islands of the archipelago are rich in groundwater, approximately 80% of the water resources in these islands (La Palma, El Hierro, La Gomera and Tenerife) are groundwater resources (Ruiz-Rosa *et al*., 2019). These groundwater resources are exploited mainly through wells and water galleries, which penetrate the subsoil in search of water from the aquifer. These excavations are in direct contact with the natural terrain and can contain high concentrations of gases that are harmful to human health, and are therefore considered extremely dangerous works.

The concern about air quality in subway works is not new, in fact, there are numerous studies carried out in the Canary Islands where the correlation between the emission of these gases and volcanic activity has been sought (Marrero *et al*., 2008; Torres-González *et al*., 2019). Numerous studies have also been carried out in various countries on airflow inside mines to control the effect of ventilation on CO_2 concentrations in coal mines in China (Wang *et al*., 2016) or, for example, in Poland, they have studied the ventilation of these mines to control the movement of cases in the event of a fire (Dziurzyński *et al*., 2017). Also, radon concentrations in mines have been studied in Poland (Skubacz *et al*., 2019), Brasil (do Carmo Leal *et al*., 2020) and Italy (Tommasone *et al*., 2011), among other countries. In the Canary Islands, several studies have been developed and they corroborate the high levels of radon found in water galleries, mainly due to the geochemical composition of the volcanic territory (Eff-Darwich *et al*., 2008; Padilla *et al*., 2013; Padrón *et al*., 2013). Also, the participation of faults, fractures or fissures in the evaluated cavities have to be considered as migration channels for the gases, a phenomenon known as "diffusion ventilation" in Spanish underground mining regulation (Reglamento General de Normas Básicas de Seguridad Minera, ITC 04.7.01, 1985).

Therefore, the objective of this analysis has been to study the incidence of radon gas, and other volcanic gases, such as carbon dioxide, and how they affect the atmosphere inside the water galleries in the Canary Islands, which are vital works for obtaining water in the archipelago.

2. Materials and methods

The Canary Islands are an archipelago, belonging to Spain, which are located in the Atlantic Ocean. The archipelago is made up of seven islands: La Palma, El Hierro, La Gomera, Tenerife, Gran Canaria, Fuerteventura and Lanzarote. The Canary Islands have a volcanic origin, which means that traditionally gaseous emanations of diverse origin have existed in the subway water catchments (Coello-Bravo *et al*., 2020). The combination of the following factors determines the composition of the air inside the gallery: characteristics of the natural emission of gases inside the gallery; forced ventilation by means of air extraction and/or injection devices, and climatic conditions (pressure and temperature) existing inside the gallery (Torres-González *et al*., 2019).

Thirteen galleries were selected on the island of Tenerife for this study. They were chosen because they were considered to have a combination of interesting gases for the study, according to previous knowledge of these galleries available from the Tenerife Island Water Council. From the data collection of the selected galleries, the following information was obtained: facilities located outside the gallery (engine rooms); facilities located inside the gallery (ventilation and water pipes); and state of conservation and

atmosphere of the gallery (temperature, humidity, presence of gases in the whole route). In order to characterize the presence of gases inside the mine, continuous measurements of carbon dioxide and oxygen were undertaken.

Also, in this study, radon gas measurements were taken in different water galleries on the islands of Tenerife, La Palma and El Hierro. La Palma and El Hierro are the youngest islands in the archipelago, and both have experienced recent volcanic eruptions. For its part, Tenerife has a complex hydro-geological system, where the water table represents the topography of the island, although there are some irregularities imposed by the geological structure of the subsoil (Santamarta & Lario-Bascones, 2015). Five galleries were selected on La Palma, four on El Hierro and nine on Tenerife (Figure 1). Water galleries are horizontal constructions inserted into the ground, varying in length but usually several kilometres long, which aim to reach the aquifer in order to extract drinking water by gravity (Custodio *et al.*, 2016).

Figure 1 - Water galleries selected in this study in the Canary Islands, Spain.

The methodology applied in this project was developed by the Spanish Nuclear Safety Council in its "*Safety Guide 11.4 Methodology for the assessment of exposure to radon in the workplace*" (CSN, 2012). The guide is the official application document for studying radon in the workplace in Spain. According to Safety Guide 11.4, studies of radiological risk linked to radon should be representative of the annual exposure of workers and, where appropriate, of the public. To this end, the results should be based on measurements with passive detectors exposed for a minimum period of three months. For this reason, the Radtrak^2 model passive nuclear trace detectors were selected for this study, since they meet all the requirements of the CSN and whose measurement range covers from 15 Bq/m^3 to 25000 Bq/m^3. These latest generation detectors consist of a radiation-sensitive film, located inside a capsule made of a special anti-static plastic that allows the entry of radon gas by diffusion. These detectors are harmless and do not interfere with people. They do not require a power supply and perform an integrated measurement for the recommended period of three months.

The measurements were conducted in representative locations of the working areas within the mine (Figure 2), where the workers spend most of their time, 50 cm above the ground. As soon as the detectors were removed after the measurement periods, they were sent to an accredited laboratory for analysis. At the laboratory, the detectors were analyzed and a report was issued for each of the detectors with the results of the radon concentration obtained.

Figure 2 - Interior of the mine (left) and passive radon detector placed in the mine (right).

Moreover, the *Fuente Santa* gallery is a historical source of thermal water located on the island of La Palma. It has a unique combination of geographical, hydrogeological and structural factors: it is only 180 metres long and is located in a southern beach of the island (Figures 3 and 4) and water emerges in six different "pools" named with the letters A to F and an external pool located next to the pithead beach named "G". These factors involve a delicate balance among the atmospheric conditions, the influence of the tides and the emergence of underground volcanic gases; in fact, each pool presents different characteristics related to dissolved salts, water temperature and gas emissions. This water facility is currently closed to the public.

Figure 3 - Interior of the thermal water gallery "Fuente Santa" on the island of La Palma.

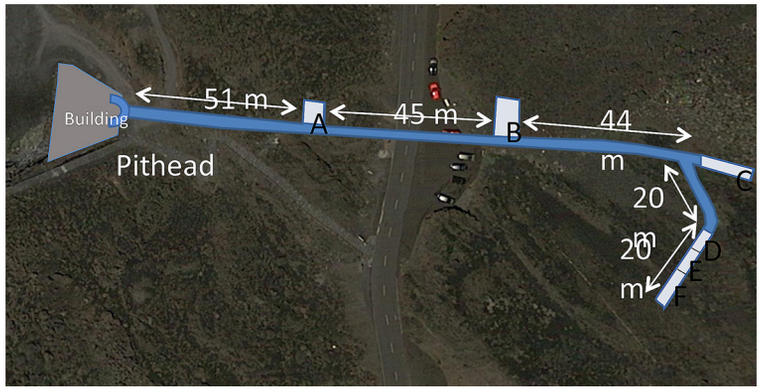

Figure 4 - Outline of the water gallery "Fuente Santa" on the island of La Palma.

In this case, measurements of CO_2 concentration were made in four points of the gallery (pools C, D, E and F) as measurements of water conductivity were made in the six pools, all the variables were also measured in the external pool (G). The devices used for this purpose were the detectors VAISALA GMT221 (with 4-20 mA output, and measurement ranges up to 20%). These detectors use the CARBOCAP sensor technology based on an electrically tuneable Fabry-Pérot Interferometer (FPI) (Figure 5).

Figure 5 - Monitoring of CO_2 measurement inside the gallery.

3. Results and discussion

The Canary Islands Mining Service supervise the safety of the “water miners”, despite the gallery owner is the unique responsible for it. In order to verify data supplied by the gallery’s owners, the Canary Mining Service made a sampling campaign in 2004, measuring work atmosphere variables in thirteen galleries. The facilities were selected trying to cover different geological and geographical environments in a first attempt to establish a risk zone map. Also, the galleries had different ventilation systems and even water transportation (open channels and closed pipes) methods.

Table 1 shows the maximum and min-

imum inside atmosphere variables measured in a point of the gallery during 8 hours work shift: CO_2 and O_2 volumetric concentration, air relative humidity and air temperature.

Table 1 - Work atmosphere parameters in 13 water galleries on the island of Tenerife (data from the Canary Islands Government, 2014).

Code	Municipality	Max CO_2 (%)	Max O_2 (%)	Max T (°C)	Max RH (%)	Min CO_2 (%)	Min O_2 (%)	Min T (°C)	Min RH (%)
TF1	Icod de Los Vinos	0.41	20.7	34.7	99.9	0.06	19.6	31.2	99.6
TF2	Arico	2.72	20.8	37.5	99.9	0.13	18.8	29.4	80
TF3	El Sauzal	0.16	21.3	21.8	99.7	0	19.9	17.3	83.6
TF4	Arico	1.23	20.7	33.3	99.6	0.05	19.7	27.6	99.6
TF5	La Guancha	0.64	20.6	20.8	99.2	0.11	19.8	18.4	93
TF6	Arico	4.51	20.5	31.7	99.6	0.05	18.4	25.9	99.4
TF7	Garachico	3.13	21.1	20.4	99.6	0.02	19.3	12.7	94.6
TF8	Santiago del Teide	0.21	21.1	12.3	99.7	0.01	20.2	9.1	79.7
TF9	Guía de Isora	1.74	21.3	20.6	99.6	0.04	20.6	15.4	84.2
TF10	Guía de Isora	1.53	21.3	18.4	99.7	0.02	20.2	13.6	99.6
TF11	Garachico	4.99	21	23.2	99.7	0.05	18.8	15.1	90.2
TF12	Fasnia	0.2	21.1	32.3	99.6	0	20.2	18.2	56.4
TF13	San Miguel	1.06	21.2	26.2	99.6	0.04	20.3	21.6	93.4

As can be seen in Table 1, casuistry is wide. At first look, geographical pattern could be suggested, as galleries TF9-TF10, TF7-TF11 and TF2-TF6 are located in the same municipalities and present some similarities in the variation rate between minimum and maximum CO_2 and O_2 concentrations. Actually, this is a simplistic approach, since the gallery TF8 is located at less than 8 kilometers from gallery TF9 and gallery TF12 is located at less than 10 km form galley TF-6.

One of the main parameters that can modify the atmosphere of the gallery is its contact with water (Soler *et al*., 2004). The extent of such modification will largely depend on some specific characteristics of the water, particularly its gas content (O_2 and CO_2).

The use of closed water pipes avoids the increase of gas-water and contributes significantly to improving the temperature and humidity conditions of the gallery. In the case of carbonic waters, the emission of CO_2 that is produced when the waters are released in the mine could be minimized if the emerging sections are isolated by means of capture devices, capable of collecting and conducting the water towards the pipe, thus avoiding contact with the atmosphere. Such a device should be equipped with a gas outlet connected to the extraction system. Also, it would be very useful to have a characterization of the atmosphere in each gallery, describing the evolution of parameters, such as pressure, temperature, humidity, concentration of different gases, characteristics of water, nature and state of conservation of the pipes, characteristics of the extraction system, etc.

Another key aspect for the gallery maintenance workers is to have portable gas detection equipment, including radon gas, because its relationship to lung cancer is high. The WHO states that exposure to radon concentrations greater than 100 Bq/m^3 increase the risk of lung cancer (WHO, 2009). However, in all the galleries of the study carried out on the islands of Tenerife, El Hierro and La Palma, the radon levels permitted by international organisations were far exceeded, reaching values of even 10.000 Bq/m^3 (Table 2).

Table 2 - Radon values obtained in the measured galleries of Tenerife, La Palma and El Hierro.

Island	Minimum average value Bq/m^3	Average value Bq/m^3	Maximum average value Bq/m^3	Uncertainty Bq/m^3
Tenerife	6,829	8,473	10,117	1,644
La Palma	2,287	3,388	4,489	1,101
El Hierro	838	1,015	1,193	178
Average Value	3,318	4,292	5,266	947

Fortunately, the work done today in the water galleries is maintenance work, which requires short, spaced-out workdays. In other words, workers do not have to spend hours inside the gallery every day, where continued inhalation of high concentrations of radon gas would be even more of a concern. However, it is necessary to know that it is common to find high levels of radon in the ground in the Canary Islands, so that if drilling work is to be carried out in a water gallery where workers are going to spend long days, radon levels should be controlled and monitored to protect their health. In experiences in other types of subway works in the islands, it has been seen that when these works are lined with gunned

concrete, the incidence of radon gas is significantly lower when compared to works without lining (Santamarta *et al.*, 2020).

Frequently, the gallery sections most affected by the presence of gases coincide precisely with the water-saturated zone. The most unfavourable cases are those of reducing waters and carbonic waters, since the former tend to balance with the gallery atmosphere by consuming oxygen, while carbonic waters release CO_2 once outcropped. Likewise, the presence of thermal waters produces an increase in the environmental temperature and humidity, which results in worsening work conditions.

Figure 6 shows CO_2 hourly mean concentrations, on a base of 5 minutes sampling, in "C" "D" "F" and "G" (exterior) water pools (Figure 4) inside the Fuente Santa gallery.

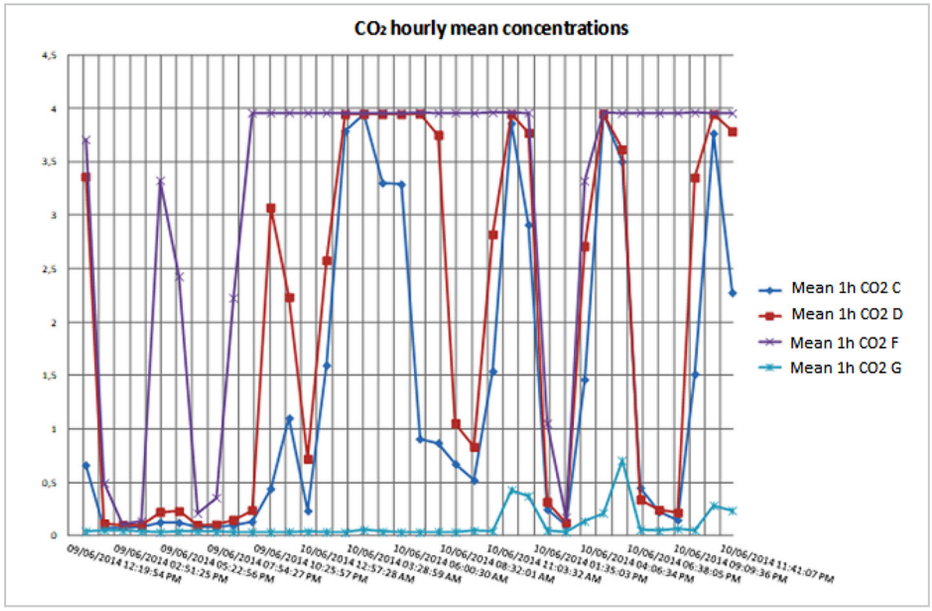

Figure 6 - CO_2 levels measured in 24 hours in four pools inside the thermal water gallery of the island of La Palma.

As can be seen, CO_2 concentrations may vary rapidly but they seem to follow a predictable time pattern, with maximum and minimum concentrations distributed in almost regular intervals for pools C and D; pool F, located on the face end of the gallery presents higher concentrations, above the sensor maximum measurement level. Meanwhile, Figure 7 shows the same CO2 hourly mean concentrations graphic but with the addition of pool "E", located between "D" and "F" pool (see Figure 4).

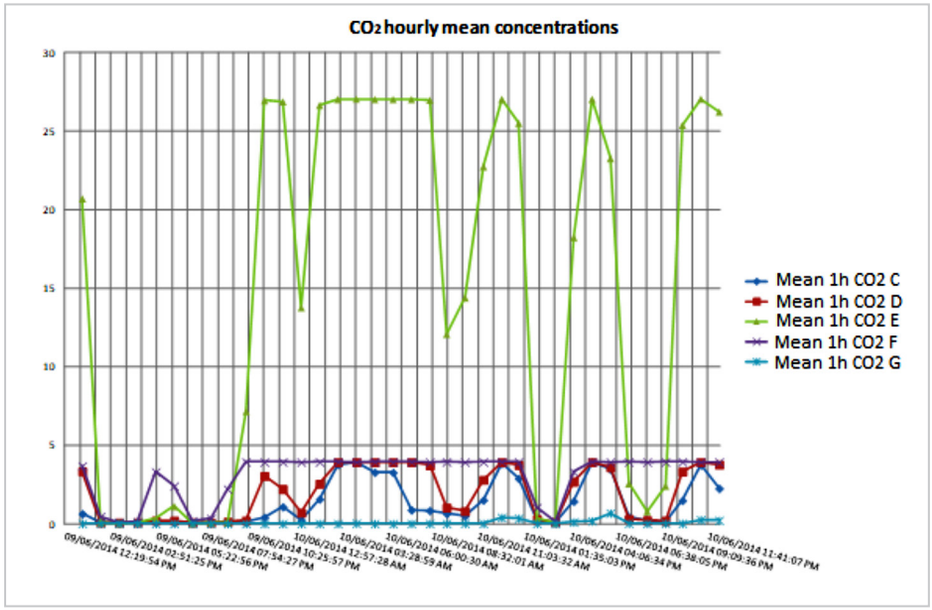

Figure 7 - CO_2 levels measured in 24 hours in five pools inside the thermal water gallery of the island of La Palma.

Figure 7 confirms a certain time pattern but it shows that it's difficult to predict the maximum value of gas concentration in the deepest pools (C, D and F). As pool F concentration at 5:22pm of June the 9th or 9:09 pm of June the 10th present the highest value of all pools, we can see pool E concentration is much higher in the rest of the episodes of gas emanation.

The periodicity of the gas emanation episodes is related to exterior atmospheric conditions, including air temperature, and barometric pressure, but these factors alone cannot fully explain the dynamics of the working atmosphere inside the gallery.

4. Conclusion

The maintenance of appropriate atmospheric conditions inside the water galleries on the Canary Islands often present important difficulties. Workers' health must be preserved, as far as carbon dioxide and radon gas are concerned. It is proposed to provide forced ventilation of all existing galleries, which would help to reduce the concentration of harmful gases.

After studying the ventilation conditions of the 13 galleries analyzed, in relation to the presence of gases and the atmospheric conditions inside them, the following sections were defined:

• The machinery installed for ventilation in some galleries, as well as the auxiliary elements, are powerful enough and are in good state of conservation. In addition, the ventilation conditions generally allow the ambient temperature in the workstations to be maintained, in agreement with Spanish legislation

• Atmospheric conditions are met in terms of CO_2 and O_2 concentration

• Atmospheric conditions inside galleries may be predictable in terms of periodicity but not in terms of concentration values. More research is needed.

• The air speed inside the galleries meets the requirements set by Spanish legislation

• There are no continuous gas monitoring systems inside the galleries, only portable detectors are used by workers, so there are no profiles that reflect the atmospheric conditions inside them.

• An air flow is observed along the upper gallery that is greater than that measured in the exhaust pipe, which is a natural flow that would occur even with the ventilation stopped. This may be due to the volcanic soil that forms the interior of the galleries and whose permeability is high.

As the Canary Islands are volcanic territories, they have geochemical properties that favor the exhalation of these gases by the rocks. Thus, the value concentrations of the gases found in our experiments, can be considered in others that present similarities, in order to protect the health of the people working in the underground installations.

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