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Estimating ambient gamma dose rate in the oil town of Pacayacu, Ecuador

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Abstract: This study estimated the ambient equivalent dose rate in the oil parish of Pacayacu, which is located in Lago Agrio, Sucumbíos province. It has experienced constant oil activity since 1980. Measurements were performed in 77 different places, including 63 closed oil wells, eight points near operating wells, three points between Pacayacu and the Aguarico River, one mining concession, and two control points. Ludlum digital meters connected to NaI(Tl) scintillation probes were used to obtain five one-minute measurements at each site. The average ambient equivalent dose rate was 0.12 $\mu Sv \cdot h^{-1}$, with values ranging from 0.05 to 0.20 $\mu Sv \cdot h^{-1}$, excluding the highest value of 0.86 $\mu Sv \cdot h^{-1}$ at one site. The annual effective dose of the external irradiation was calculated using the average ambient equivalent dose rate at each sampling point. One closed well coded "PPC(SHR-04)" had an annual effective dose of 1.51 $mSv \cdot y^{-1}$, that exceeded the public exposure limit established by national law (0.3 $mSv \cdot y^{-1}$) and the 1 $mSv \cdot y^{-1}$ limit defined by the IAEA. Sweeping measurements around this well indicated that the elevated gamma radiation originated from pipes delimiting the well, point to the presence of NORM internal scales. Consequently, these results highlight the potential influence of oil activity on the annual effective dose. In oil areas, the focus should be on the importance of proper waste management to prevent exposure to NORM, avoid internal contamination and environmental pollution.

Keywords: Ambient gamma dose equivalent rate, Oil industry, NORM and TENORM, Waste management, Ionizing radiation.

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Estimación de la tasa de dosis gamma ambiental en la ciudad petrolera de Pacayacu, Ecuador

Resumen: Este estudio estimó la tasa de dosis equivalente ambiental en la parroquia petrolera de Pacayacu, ubicada en Lago Agrio, provincia de Sucumbíos. Ha experimentado una actividad petrolera constante desde 1980. Se realizaron mediciones en 77 lugares diferentes, incluyendo 63 pozos petroleros cerrados, ocho puntos cercanos a pozos en operación, tres puntos entre Pacayacu y el río Aguarico, una concesión minera y dos puntos de control. Se utilizaron medidores digitales Ludlum conectados a sondas de centelleo de NaI(Tl) para obtener cinco mediciones de un minuto en cada sitio. La tasa de dosis equivalente ambiental promedio fue de 0,12 $\mu Sv \cdot h^{-1}$, con valores que oscilaron entre 0,05 y 0,20 $\mu Sv \cdot h^{-1}$, excluyendo el valor más alto de 0,86 $\mu Sv \cdot h^{-1}$ en un emplazamiento. La dosis efectiva anual de irradiación externa se calculó utilizando la tasa de dosis equivalente ambiental promedio en cada punto de muestreo. Un pozo cerrado codificado «PPC(SHR-04)» tenía una dosis efectiva anual de 1,51 $mSv \cdot y^{-1}$, que supera el límite de exposición pública establecido por la legislación nacional (0,3 $mSv \cdot y^{-1}$) y el límite de 1 $mSv \cdot y^{-1}$ definido por OIEA. Las mediciones de barrido alrededor de este pozo indicaron que la elevada radiación gamma se originó en las tuberías que delimitan el pozo, lo que apunta a la presencia de escamas internas de NORM. En consecuencia, estos resultados ponen de manifiesto la posible influencia de la actividad petrolera en la dosis efectiva anual. En esta zona petrolera, el enfoque debe estar en la importancia de una gestión adecuada de los residuos para prevenir la exposición a NORM, evitar la contaminación interna y la contaminación ambiental.

Palabras claves: Tasa de dosis equivalente de gamma ambiental, Industria petrolera, NORM y TENORM, Gestión de residuos, Radiación ionizante.

1. INTRODUCTION

Ecuador has the fourth-highest oil reserves in Latin America and the Caribbean, with approximately 8.27 billion barrels [1]. In 2021, it was ranked fifth among oil producers in South America [2]. The country experienced a significant change in its oil activities starting in the 1970s. This crucial change was largely due to the development and implementation of the Trans-Ecuadorian Oil Pipeline System, which plays a fundamental role in promoting oil exports through the Balao Esmeraldas Maritime Terminal, transporting more than 5000 million barrels of crude oil from the eastern provinces of Sucumbíos, Orellana, and Napo [3]. Oil and gas exploitation accounts for 11.3 % of the national Gross Domestic Product [4]. Extractive activities were developed with little environmental control, despite the existing technology and qualified personnel. Ecuador reported having 3,568 closed oil wells, which are considered 'pollution sources' in the oil and gas sector, there are 4675 contaminated sites, most of them located in the Sucumbíos (with 2776) and Orellana (1646) provinces of the Amazon (Figure 1). For example, Texaco left 714 buried oil pools that have resurfaced over the years [5].

Ecuador boasts one of the greatest biodiversity in the world, making it common for areas affected by oil and gas exploitation to host a wide variety of flora and fauna, which deteriorate year after year due to the installation of camps and oil wells. One such location is the town of Pacayacu, which has a long history of colonization and oil exploitation (1980-1990) [6]. The selected area is characterized by a highly concentration of oil wells and pipelines, and contamination can spread to dispersed sites along the Aguarico River, including the Cuyabeno Fauna Production Reserve [7]. Pacayacu, where the "Libertador" oil field exploitation is higher, has experienced oil spills. The consequence is contamination of soil, water sources (rivers and streams), and vegetation, causing long-term damage to ecosystems [8,9]. Despite this, few articles have reported severe contamination from years past, such as pollution in water wells and crops and increased air pollution due to the emission of greenhouse gases [6].

Researchers are also concerned about occupational safety and the environment, particularly the waste generated, such as produced water and solid waste (scale and/or sludge) [10]. This type of waste is an important source of naturally occurring radioactive materials (NORM) and technologically enhanced naturally occurring radioactive materials (TENORM) [11,12]. A preliminary inventory developed by the National Regulatory Authority, Subsecretaria de Control y Aplicaciones Nucleares (SCAN), identifies the oil industry as the primary industry generating NORM and TENORM in Ecuador [13]. One study corroborates the presence of NORM in sludge, scales (in drill pipes, valves, pumps, storage tanks, separators, and old wellheads), and formation water to the south near our study area, where the annual effective dose rate is below the recommended exposure limit for the public [14].

Gamma radiation emitted by ^{40}K and decay chains of ^{238}U and ^{232}Th present in the soil primarily contributes to external exposure to natural ionizing radiation in the population [15]. Gamma radiation levels depend on the concentration of radionuclides, which in turn depend on the geological formation and soil type, with high levels found in geologies composed of igneous rocks (granite) and rocks with high silica concentrations [16]. Therefore, the population and workers in the oil, gas, and mining industries may be exposed to high doses of gamma radiation, such as near uranium deposits and other unexpected sources [11,12,17,18]. These industrial activities result in planned exposures, primarily influenced by the extraction and concentration of NORM during production [19]. By monitoring the gamma radiation, among other parameters, according to the national law [20], which establishes the effective dose values of 1 $mSv \cdot y^{-1}$ and 0.3 $mSv \cdot y^{-1}$, for workers and members of the public, respectively.

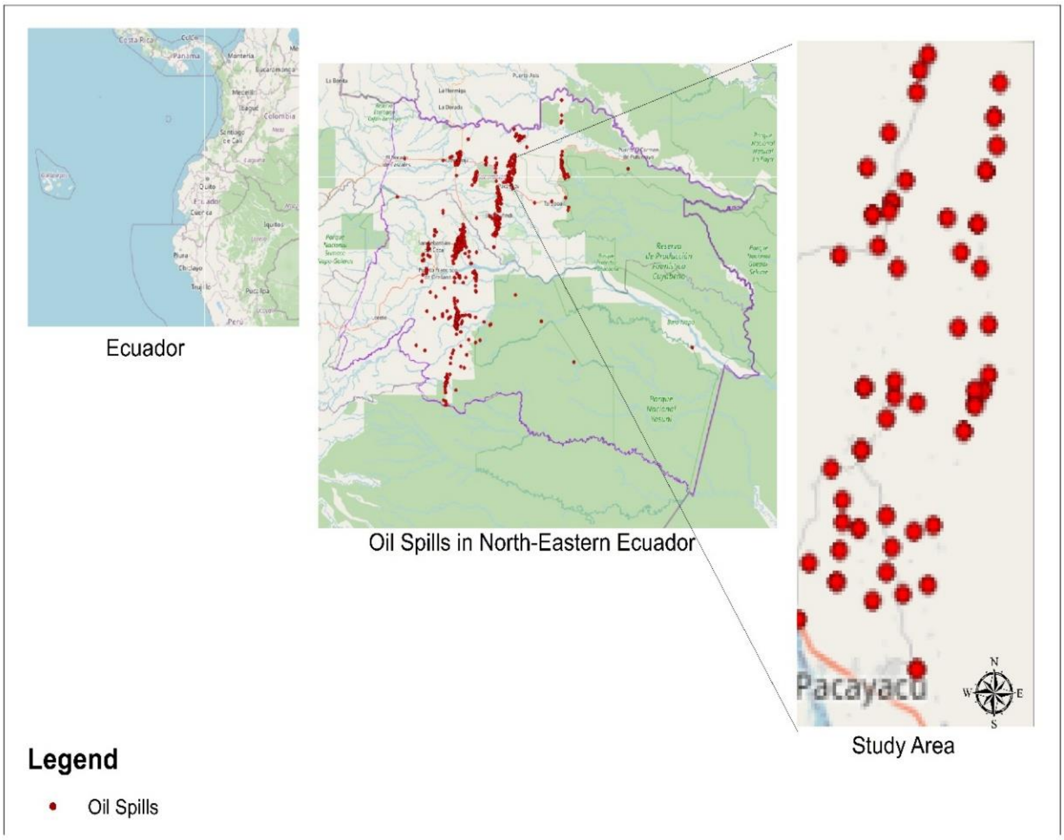
In this study, the ambient equivalent dose rate was assessed in closed oil wells in Pacayacu, an oil-producing region, which may indicate contamination from oil activities. A point of radiological interest was identified that exceeded the public exposure limit established by the national law and the limit suggested by the IAEA. The results of this study will stimulate the implementation of future radiometric studies at other oil sites and will serve as input for compliance monitoring by the regulatory authority SCAN.

2. MATERIALS AND METHODS

2.1. Study area

The oil town of Pacayacu is located in the Lago Agrio canton of Sucumbíos province, in northeast of the Amazon region of Ecuador, where oil spills have occurred (Figure 1). The study area lies within the Curaray geological formation, which consists of clay, tuffaceous shale, and gypsum [21]. Its geographical coordinates range from 0°05'32.1" N to 0°03'0.9" S in latitude and from 76°33'15.4" W to 76°36'30.2" W in longitude, encompassing a territorial area of approximately 96.56 km2. As mentioned above the "Libertador" oil field is one of the areas with the highest oil activity within the Amazon district, with Pacayacu recording the second-highest greenhouse gas emissions and black carbon production after Shushufindi [6]. According to the 2022 census, the total population of Pacayacu was 3,357 inhabitants [22].

Figure 1: Location map of the study area



Source: Data from the MONOIL study. Modified from figures available at http://geode-utils.univ-tlse2.fr/lizmap-web-client-2.9.4/lizmap/www/index.php

2.2. Measurement of ambient gamma dose equivalent rate

To meet the objective of this study, gamma radiation measurements were performed in March and August 2023, and April 2024. The sites of interest were identified as follows: 63 closed oil wells; eight points located approximately 100 m from the wells in production; three points between Pacayacu and the Aguarico River; one in a mining concession of arid and stony materials; and two control points located approximately 1 km from the nearest oil well. The ambient equivalent dose rate measurements at the 63 closed wells consisted of five one-minute measurements, taken 1 m above the ground and 1.5 m horizontally from the wellhead for statistical purposes [18,23], and to obtain an average ambient equivalent dose rate for each site. Measurement values near the wellhead were below the limit established by the national standard. Monitoring of the remaining points was conducted similarly, with five measurements, each lasting one minute, at 1 m above ground. The annual effective dose rate was subsequently calculated using the equation (1) reported by UNSCEAR, which considers factors such as the time spent outdoors and the occupancy factor, providing a more accurate estimate of radiation exposure for the general population in the study area [24].

$$AED = D * T * F/10^3 \quad (1)$$

Where D is the ambient equivalent dose rate ($\mu Sv \cdot h^{-1}$), T is the number of hours per year (8760 $h \cdot y^{-1}$), and F is the outdoor occupancy factor (0.2). The results indicated the presence of NORM in the study area due to oil activity.

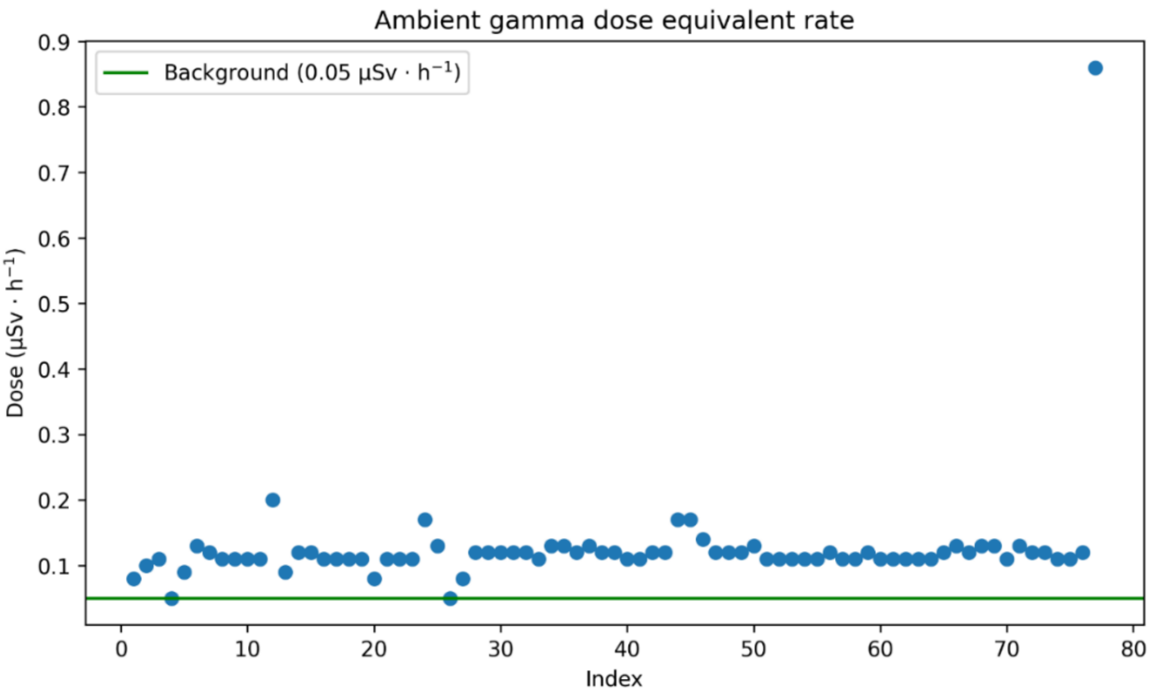
Effective dose values exceeding the recommended public exposure limit established by the national law and the suggested values by the IAEA were considered cases of interest. A radiation sweep monitoring of the ground and metal structures (wellhead and enclosure) of the oil well was conducted. It is important to note that there are strict access restrictions to wells during reconditioning and operation.

To obtain measurements at the 77 sites, Ludlum digital meters (models 3003 and 30) were connected to a Ludlum NaI(Tl) scintillation probe (model 44-10). The model 3003 series is a multi-detector scintillation/SCA meter designed for the study of alpha, beta, gamma, or neutron radiation, with factory calibration issued on 23-06-2022 and regulatory calibration from SCAN on 28-02-2024. The digital meter, Model 30, was configured to measure gamma radiation (https://ludlums.com/products/all-products/product/model-30), with factory calibration issued on 11-11-2022 and regulatory calibration from SCAN on 28-02-2024. The typical sensitivity of the probe is 900 cpm per $\mu R \cdot h^{-1}$ (0.01 $\mu Sv \cdot h^{-1}$). The scintillation probe is a low-level gamma radiation detector with a wide range of response energies from 60 keV to 2 MeV [25]. This range covers the gamma energy emitted by the terrestrial radionuclides [26].

3. RESULTS AND DISCUSSIONS

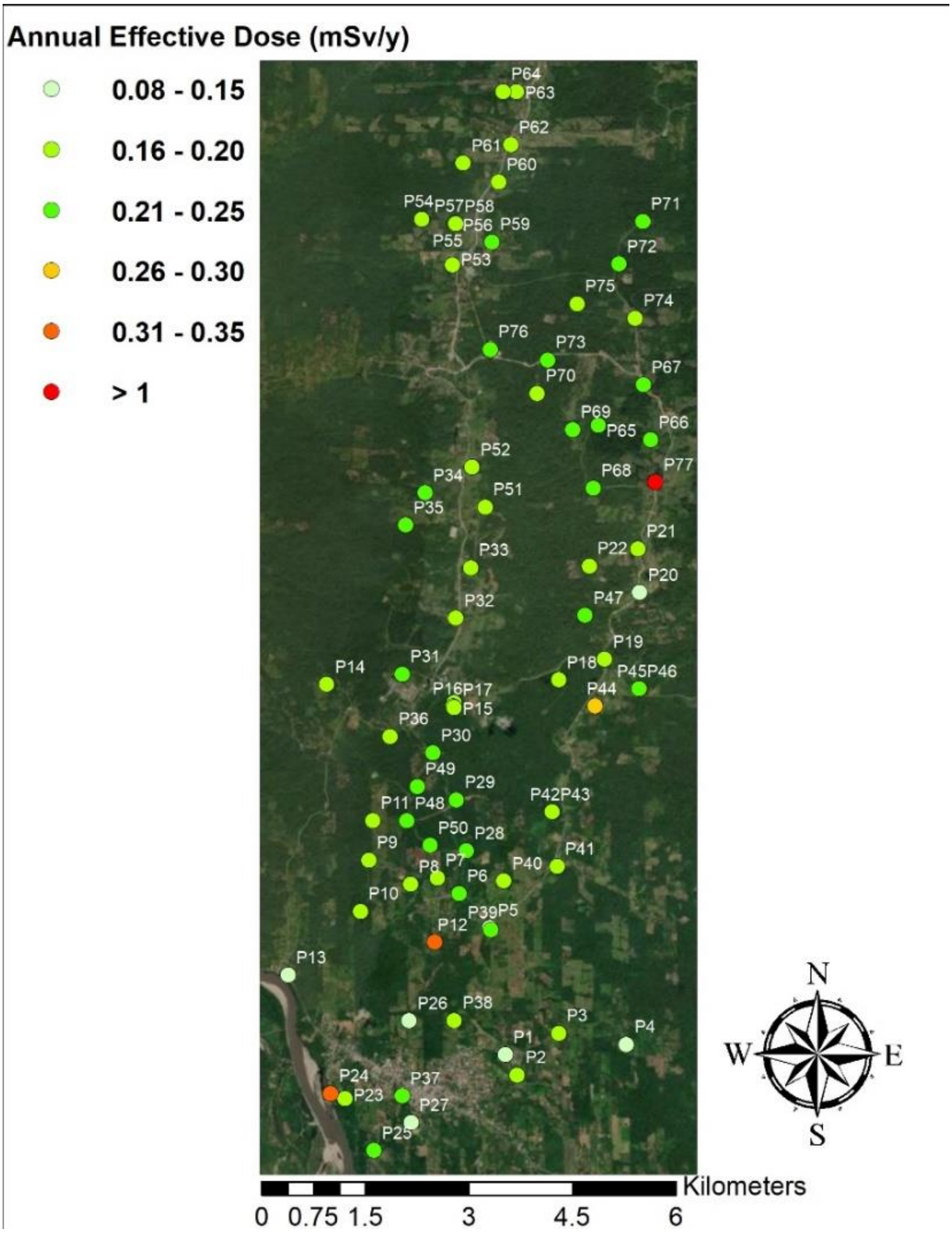
The results of the ambient equivalent dose rate obtained in this study are shown in Figure 2. Excluding the highest value of 0.86 μSv·h⁻¹ from sampling point 77 (coordinates 0°02'18.3" N and 76°33'27.1" W), the values vary between 0.05 and 0.20 μSv·h⁻¹, with an average of 0.12 μSv·h⁻¹. The two control points, P4 and P26, yielded the lowest value of 0.05 μSv·h⁻¹ (with the green line representing the background radiation, as shown in Figure 2), followed by points monitored outside of operating oil stations, which fall in the range of 0.08 to 0.10 μSv·h⁻¹. The majority of closed wells monitored ranged from 0.11 to 0.14 μSv·h⁻¹, with two points at 0.17 μSv·h⁻¹ and one at 0.20 μSv·h⁻¹ (coordinates 0°01'18.7" S and 76°35'10.4" W). The mining concession of arid and stony materials revealed a mean ambient equivalent dose rate of 0.17 μSv·h⁻¹. Gamma ray dose rates measured at oil plants in Algeria, where the oil industry is the major source of NORM waste, show doses between 0.8 and 76 μSv·h⁻¹ [27]. This indicates that oil industrial activities can influence ambient radiation levels in the surrounding environment.

Figure 2: Ambient gamma dose equivalent rate



The integration of NaI(Tl) scintillation detectors with Ludlum digital meters is a reliable approach for assessing the gamma radiation levels around oil wells and construction material mines. Oil activity involves handling radioactive byproducts, which can potentially increase the exposure of workers to gamma radiation, and the contamination of the environment by waste increases the exposure of the surrounding population. Based on the results obtained, the mean ambient equivalent dose rate for each sampling point was used in eq. (1) to calculate the annual effective dose, which was color-coded and superimposed on the study area, as shown in Figure 3. The study area is considered to have the same geological formation and does not have significant altitude variation (256–308 m above sea level). It is important to emphasize that the town of Pacayacu is near zero latitude (the equatorial line), a region where the influence of cosmic rays is lower than at higher latitudes. Therefore, terrestrial radiation is the dominant component of external radiation exposure. Figure 3 shows the annual effective dose to which the study population was exposed, indicating that factors such as oil activity can increase the levels of natural ionizing radiation.

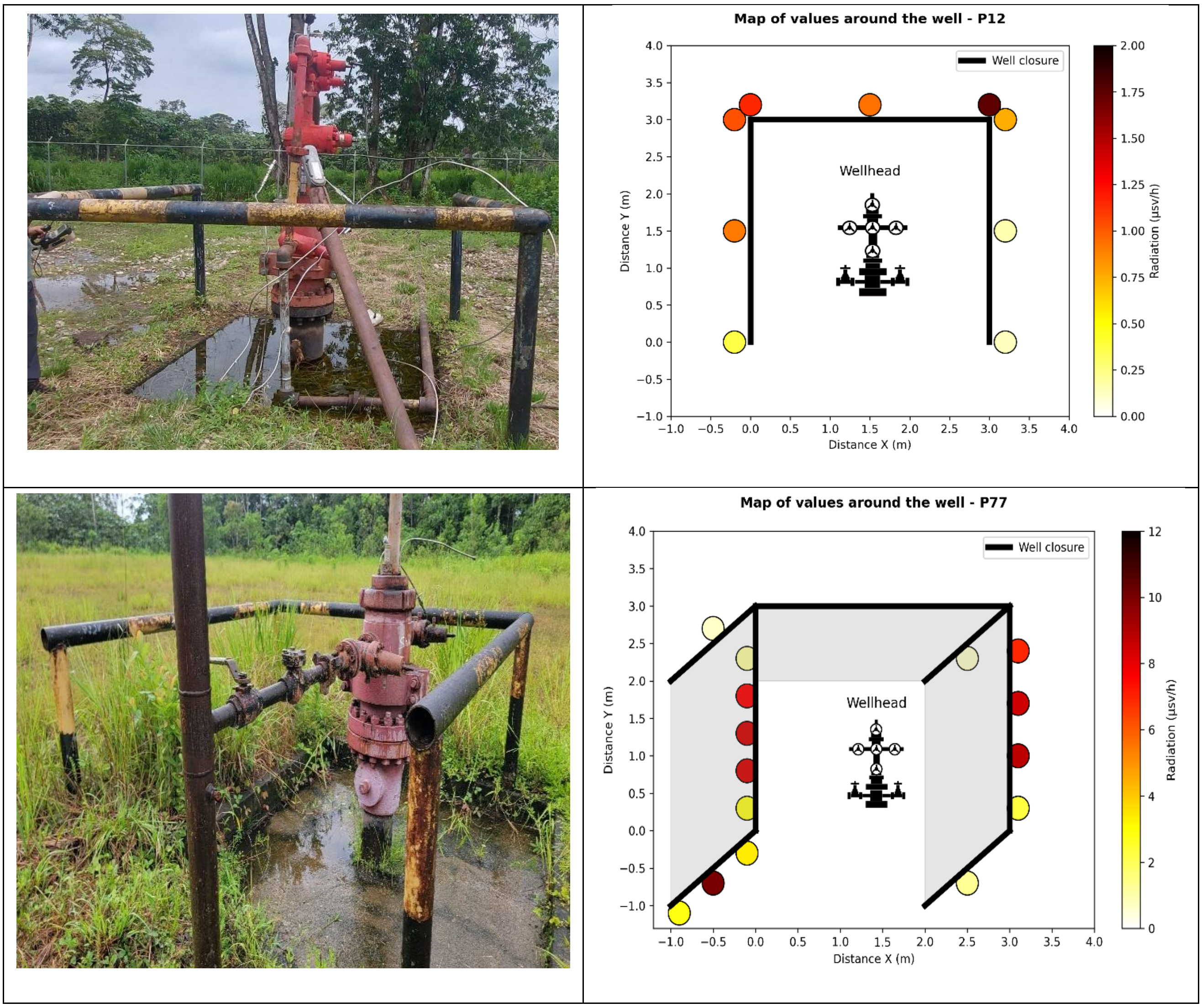
Figure 3: Annual Effective Dose



The annual effective dose at points 12 and 77 is 0.35 and 1.51 $mSv \cdot y^{-1}$, respectively. Both exceed the public exposure limit of 0.3 $mSv \cdot y^{-1}$ established by national law. The highest value of the annual effective dose occurred in the closed well coded "PPC(SHR-04)" at site

P77. In this study, this annual effective dose is of particular interest from a radiation protection point of view; that exceeded the public exposure limit established by national law and the 1 $mSv \cdot y^{-1}$ limit defined by the IAEA. Sweep measurements of the oil wells “HVI-22”at site P12 and "PPC(SHR-04)" at site P77 are shown in Figure 4, with values from 0,20 to 10 $\mu Sv \cdot h^{-1}$, corresponding to measurements taken 5 cm from the enclosure metal pipes. This variability is possibly due to the accumulation of radioactive material in certain sections of the pipes used in oil exploitation, indicating the presence of NORM contamination inside the pipes.

Figure 4: Sweep measurements of the oil well at sites P12 and P77



4. CONCLUSIONS

Most of the closed wells monitored showed gamma radiation levels double those found at the control points, which may indicate contamination from oil activity. This increases the ambient equivalent dose rate in areas where waste management is not performed according to national standards.

A point of radiological interest was found, corresponding to oil well coded "PPC(SHR-04)" at site P77, with an annual effective dose value of 1.51 $mSv \cdot y^{-1}$, exceeding the annual effective dose limit for the public established by national law. Sweep measurements around the oil well structures determined that the source of the elevated gamma radiation comes from pipes that delimit the well.

This finding confirms the presence of the NORM inside the tubes, as has been reported in oil fields located south of the study area. This result highlights the influence of industrial activity on the annual effective dose and underscores the importance of conducting comprehensive evaluations for effective waste management in oil area, as well as the proper closure of wells, considering that their wastes are NORM-contaminated.

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CONFLICT OF INTEREST

All authors declare that they have no conflicts of interest.

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