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Integration of Isotopic and Nuclear Techniques to Assess Water and Soil Resources Degradation. A Critical Review

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Abstract: The isotopic and nuclear techniques discussed, namely: Fallout Radionuclide, Fingerprint, and Isotope Hydrology, are linked to the evaluation of soil and water degradation processes. A traditional literature review was conducted to gain the most comprehensive understanding of both the current state of the art and the subject matter, with the aim of proposing a hypothesis that integrates the synergistic convergence of these techniques in order to offer results that are more reliable. A case study is presented as a synthesis of the preceding discussion.

Keywords: Fallout Radionuclide; Fingerprint; Isotope Hydrology; Soil degradation; Water resources degradation; Integrated nuclear techniques.

1. Introduction

Over the past few decades, environmental concerns have grown; climate change, pollution control, biodiversity preservation, and management of soil and water resources are public concerns on a global scale (Ahmadov, 2020). Climate change is expected to cause increased soil erosion globally, affecting ecosystem services and human welfare, demonstrating an increasing global trend in soil erosion towards the end of the 21st century (Eekhout and De Vente, 2022). Climate change modifies precipitation patterns, soil moisture and runoff, causing an increase in temperature, increasing the water demand, and creating situations of water stress (Bárcena et al. 2020).

Water sustains all forms of life on planet Earth, and the availability of fresh water for living beings is decreasing (Singh, 2021). Global water is one of the main drivers of economic development and a source of contention and conflict. Although most of it is salty and not suitable for human consumption (Chen et al., 2020) due to its contamination, it has become a serious environmental problem on a global scale (Ashouri and Rafei, 2021). In the current scenario, with the growing demand for fresh water, supplies of uncontaminated and disease-free water are increasingly scarce, this being the environmental compartment most vulnerable to impacts of various industrial activities, in addition to identifying heavy metal pollution as a real risk for aquatic environments and human health due to toxicity, persistence and biological accumulation (López et al., 2019).

The COVID-19 pandemic generated greater public awareness of the close relationship between the environment and human health, representing a window of opportunity to implement necessary actions that preserve or restore soil health (Zabaloy, 2021). Soil is a vital resource for society in general and an important determinant of the economic status of nations (Zinck et al., 2023). It takes up to

2000 years to form one inch of soil, and this soil can be eroded by wind or water in a single storm. If soil developed over millennia is not conserved, it can be lost within a single human generation; however, soils can be used repeatedly using appropriate conservation practices (Moorberg and Crouse, 2021). The United Nations Environment Program (UNEP) emphasizes land degradation as a significant environmental challenge due to its association with water conservation, which is vital for sustainable food production and water supply (UN., 2022; UN-UNEP, 2022). Food security depends on the protection of soil and water, requiring the use of innovative ways to achieve the Sustainable Development Goals (SDGs). Several major global policy frameworks have been published over the past decade, introducing the SDGs and land degradation neutrality, with specific lines on water and targets for land and soil health (FAO, 2021; UN, 2022). In the new world vision of One Health, the soil is exposed as a fundamental environmental compartment because it provides the ecosystem services that sustain life on Earth (Kendzior et al., 2022; FAO, 2023), and the contribution of soil to achieve these services is framed in soil health as the most effective current way to promote soil in an inter- and transdisciplinary context (Bouma, 2022; Hussain et al., 2022). Also, it is important to recognize that the global process of soil water erosion has been identified as a net source of Carbon in the atmosphere, influencing the redistribution of soil organic carbon and the positive or negative fluxes of CO_2 into the atmosphere (Aguirre-Salado et al., 2023).

The United Nations General Assembly recognized in 2022 that all humanity has the right to live in a clean, healthy and sustainable environment. In order to achieve this, we have to open the doors to new approaches and solutions at different scales, which will help us to move towards a sustainable future in which both people and nature can thrive (WWF, 2020). Water erosion of the land surface of the globe by rainfall and associated fluvial processes and the transfer of the mobilized sediment to the oceans by rivers must be seen as an integral part of the natural functioning of the Earth system (Golosov and Walling, 2019). As sediment produced by erosion reduces water quality, it is imperative to determine the sources of sediment runoff to prevent it from reaching river systems, lakes, and water reservoirs. It is essential to improve the efficiency and effectiveness of soil and water resources management, particularly conservation strategies, by identifying critical areas prone to erosion.

The International Atomic Energy Agency (IAEA), through the Joint Division, together with the Food and Agriculture Organization (FAO) of the United Nations, assists its Member States in applying nuclear techniques to alleviate challenges in food safety, food security and sustainable agricultural development. The Soil and Water Management and Crop Nutrition Subprogramme, within the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture, has made significant contributions to the development of isotopic techniques for the assessment of soil degradation and the development of efficient soil and land conservation approaches. These techniques include Fallout Radionuclides (FRN) such as ^{137}Cs, ^{210}Pbex, ^{7}Be, and $^{239+240}$Pu, as well as ^{13}C stable isotope and Compound-Specific Stable Isotope analyses (CSSI). The developed methodologies have been subsequently disseminated in developing countries by the IAEA's Technical Cooperation Program to assist Member States in adopting climate-smart agriculture and reduce soil degradation that poses a threat to food security and the environment (Mabit et al., 2018b). The Isotope Hydrology technique (IH) is proven to be a very useful scientific-technical tool to evaluate the degradation of water resources (Valdivieso et al., 2021).

In defense of the harmonious and continuous development of isotopic and nuclear techniques that support the evaluation of degradation of soil and water resources, particularly those referred to as FRN, Fingerprint (FP) and IH, a traditional literature review was carried out to know both "the state of the art and the state of the matter" regarding the conception of its application and the way of its use, analyzing whether they are combined or integrated in their use or if they are developed in isolation in search of particular results on a single type of degradation (soil or water).

The selection of the research works took into account the timeliness of their completion. The search for scientific articles was carried out by consulting several databases, such as the Web of Science, Scopus, Scientific Electronic Library Online (SciELO), ResearchGate, Google Scholar and others. The search of the current studies covered the period 2018-2024. Publications were reviewed

to establish research trends, referring to how researchers approach soil and water source degradation assessments through the application of three nuclear and isotopic techniques (FRN, FP and IH).

Based on these criteria, it can be established as a hypothesis that "It is possible to integrate, sequentially, using the synergistic convergence of isotopic and nuclear techniques, e.g., FRN, FP and Isotopic Hydrology, and take advantage of the results of erosion and sedimentation obtained by radionuclide concentrations (as primary data from the analysis of the tracer fingerprint used) and the results of both contributions (as input data to the analysis of flow dynamics) to evaluate processes that degrade soil and water resources, reducing their impacts on terrestrial and aquatic ecosystems".

2. Use of the Universal Soil Loss Equation and Isotopic and Nuclear Techniques to Assess Soil and Water Resources Degradation

Erosion, as a process relevant to agricultural lands and water resources, must be critically studied. The integrated study of its cycle, transport and accumulation of sediments, facilitates the understanding of its dynamics in the landscape (Peralta et al., 2020).

2.1. Use of the Universal Soil Loss Equation to Evaluate Soil Degradation

Techniques for the direct or indirect measurement of water erosion, such as Geographic Information Systems (GIS), erosion nails, erosion plots, sediment traps, etc., and the universal soil loss equation have been widely applied worldwide. Their practical use shows that they require a lot of effort and time, and that not all the techniques provide information on the spatial distribution of erosion. The universal soil loss equation (USLE), and its family of later models: the revised equation (RUSLE) (Kaushik and Santasmita, 2020) and the modified equation (MUSLE) (Benavidez et al., 2018; Yoon et al., 2021), uses default values to determine rainfall erosivity and soil erosion susceptibility factors. This leads to estimation errors that make it necessary to adjust the equation according to the actual state of the soil under study. (Valdivia-Martínez et al., 2022). However, the use of these equations, such as RUSLE, is now commonplace. Among many other works that apply these equations, can be mentioned the research by Belayneh et al. (2021), who use the RUSLE equation to understand the dynamics of soil loss and sediment production from uncalibrated basins and thus design flood and land resource management strategies in regions where rivers cause extensive land degradation and frequent flooding. The works of Fang (2021) use the RUSLE equation by integrating remote sensing images to explore temporal changes in cultivated land, soil erosion, and the loss of its organic carbon. Recent works (Nigussie et al., 2022) use the RUSLE with GIS to examine the dynamics of soil loss, the potential for sediment production and identify critical points of erosion. Also, Stefanidis et al. (2022) implements the soil erosion prediction model with RUSLE using free access geospatial data and computing processes to model the rate of soil loss with respect to species richness, habitat types and their conservation status in protected areas. Most recent works by Muñoz et al. (2023) applies the RUSLE model and GIS to quantify and analyze the spatial redistribution of water erosion in different land covers in the mid-upper Basin of the River Mira in Ecuador. Also in Ecuador, Jaya-Santillán (2023), based on the USLE method, and using GIS, models the erosion rates in the River Muchacho. Latest works by Mesfin and Abebe (2023) apply the Soil and Water Assessment (SWAT) model to identify critical areas of soil erosion and sediment production to select effective watershed intervention techniques for environmental protection.

Isotopic and nuclear techniques related to FRN, FP using CSSI and IH are useful tools to evaluate the degradation of soil and water resources. These techniques play an important and unique role in providing essential information for developing strategies to improve land and water use efficiency in agriculture, providing solutions to mitigate degradation and increase water scarcity (Sobhana et al., 2021). Modeling watershed management practices plays an important role in reducing soil erosion, land degradation and sediment production in the watershed. It is vital for environmental protection authorities, decision-makers and the scientific community to undertake intervention techniques for sub-basins with serious points of soil erosion.

2.2. The FRN Technique for Assessing Soil and Water Resources Degradation

Currently, techniques using environmental radionuclides such as FRN, including beryllium-7 (^{7}Be), cesium-137 (^{137}Cs) and excess lead-210 (^{210}Pb), are worldwide used to determine soil erosion/deposition rates in the landscape and in surface water bodies. These isotopic techniques are accessible and affordable tools to evaluate spatial and temporal patterns of soil erosion (Brandt et al., 2018a; Mabit et al., 2018a, b). The use of FRN continues its development worldwide, which can be evidenced by the observation of dissimilar investigations where (^{7}Be), (^{137}Cs), (^{210}Pb$_{ex}$) and $^{239+240}$Pu are applied in many parts of the world, depending on the time scale of the study. From all available FRNs, the ^{7}Be is the only soil tracer that can obtain short-term soil redistribution information.

Among many other investigations conducted, research by Velasco et al. (2018) in Haiti to document soil redistribution rates associated with traditional farming practices can be mentioned. Brandt et al. (2018-a) developed important work integrating CSSI and FRN to track land-use type-specific net erosion rates in a small tropical watershed. Mabit et al. (2018b) showed the IAEA/FAO support and intention to develop joint methodologies to combat soil degradation and exhibits FRN and CSSI techniques as efficient tools for these assessments. Torres (2019) used the FRN nuclear technique to document soil redistribution in the landscape and used CSSI to identify sedimentary sources in central Argentina. Khodadadi et al. (2019), in order to reduce the loss of fertile soil from rainfed croplands on steep slopes, used ^{137}Cs and ^{210}Pb$_{ex}$ measurements to evaluate the effectiveness of soil conservation practices in controlling soil erosion in Kouhin, Qazvin province of Iran.

This naturally occurring cosmogenic isotope was first used in the late 1990s and advances in recent decades now allow investigation of erosion processes not only during extreme weather events of short duration, but also over prolonged periods of up to several months (Mabit et al., 2019). La Manna et al. (2019) used FRN (^{137}Cs) to study the medium-term erosion processes in volcanic soils of Andean Patagonia; the results confirmed the potential of this technique for assessing erosion processes. Gaspar Leticia et al., (2019b; 2020a), studied the spatial variability of soil nutrients in Mediterranean mountain agroecosystems combining complex land uses and steep topography in order to assess nutrient fate, understand the potential impact of soil erosion on nutrient redistribution across landscapes, and also characterize the lateral mobilization of soil organic and inorganic carbon along topographically driven transects over a period of four decades in a subhumid karst area of northern Spain.. The spatial distribution of the fallout radionuclides was conducted by Gaspar et al. (2021) to determine the mass activities of fallout (^{137}Cs, ^{210}Pb$_{ex}$) and lithogenic radionuclides (^{238}U, ^{226}Ra, ^{232}Th, and ^{40}K) and to evaluate the main controls affecting their spatial variations in the catchment of north-eastern Spain.

A work developed by Khodadadi et al. (2020), in western Iran and southern Italy in order to assess the potential of using ^{7}Be measurements to estimate soil erosion on short time scales exposes that there is still a need for further work to evaluate the feasibility of using ^{7}Be in different areas and under different land uses or vegetation covers. Gharibreza et al. (2020) applied the ^{137}Cs nuclear technique to estimate soil redistribution rates on deforestation-induced land uses in Golestan Province, Iran. In northern Spain, Gaspar et al. (2020), used ^{137}Cs inventories to characterize organic and inorganic lateral carbon mobilization and its influence on water erosion. Yoon et al. (2021) estimated soil erosion and sedimentation on steeply sloping agricultural land enabling action for soil conservation. In China, Zheng-an et al. (2021), applied radioactive radionuclides (FRN) such as ^{137}Cs y ^{210}Pb, as a rapid and economical tool to estimate erosion rates in a wide range of spatial and temporal scales. Foucher et al. (2021) summarized the combined use of ^{137}Cs and ^{210}Pb$_{ex}$ isotopes to establish the chronology of sediment cores, providing a specialized synthesis with a unique worldwide compilation for the characterization of FRN sources and levels on a global scale. It provides a reference of ^{137}Cs peak attribution for improved dating of sediment cores and outlines the main issues that deserve attention in future research, as well as the regions where additional ^{137}Cs fallout investigations should be carried out as a priority.

To understand the effect of past practices and current agricultural management, Lizaga et al. (2022) combined the strength of empirical data and spatially distributed modelling in a medium-sized catchment, representative of agroforestry landscapes of NE Spain, developing an ensemble technique composed of ^{137}Cs - derived soil redistribution rates with specific point values and a grid-

based setup calibration for the WaTEM/SEDEM model. Research conducted in Palestine by Houshia et al. (2022), used the FRN technique with ^{137}Cs for the first time to evaluate the impact of terracing on soil erosion and deposition rates in the northern West Bank. A research carried out in Cuba by Llerena et al. (2022) showed the application of FRN in a national demonstrative site for soil, water and forests conservation, using ^{137}Cs to determine the impacts of soil erosion and the feasibility of measures taken for its conservation and improvement.

Current works, as the investigation of Hamza et al. (2023) in northern Morocco, evaluated the impact of cropping systems based on zero tillage on soil erosion using two indicators: le Biossonnais soil aggregate stability test and the activities of ^{7}Be and ^{137}Cs radionuclides using FRN. Another work, carried out by Porto and Gallegari (2023) based on the use of ^{137}Cs, confirmed that over the past four decades, theoretical models have proven to be very effective in identifying areas at risk of land degradation. Khorchani et al. (2023) studied the effects of cropland abandonment and post-land abandonment management (through natural revegetation and afforestation) on soil redistribution rates using fallout ^{137}Cs measurements in the Araguas catchment in Spanish Pyrenees. The work developed by Gharibreza et al. (2023), applied ^{137}Cs as a tracer, to estimate the impacts of various silvicultural systems on soil redistribution and achieve greater efficiency in their conservation in Iran. Kumar et al. (2023), in the Himalayan hills and mountains, used ^{137}Cs FRNs for reliable measurement of long-term soil erosion rates in order to suggest suitable conservation measures. Cabrera et al. (2023) combined the use of ^{137}Cs and ^{210}Pbex to study soil redistribution rates and the variability of lithogenic radionuclides by contrasting two watersheds with different land uses in the Uruguayan Pampa grassland. Wang et al. (2023) used ^{137}Cs and soil organic carbon inventories from watersheds spanning different climates in order to identify the relationship between climate change and erosion-induced disturbance of soil organic carbon cycling. Gaspar et al. (2023) utilized two nuclear techniques, cosmic-ray neutron sensors (CRNS) and fallout ^{137}Cs, confirming that the integration provides a more comprehensive understanding on how water content varies in soils, its relationships with other soil properties, and how soil moisture affects the process of soil degradation.

2.3. The FP Technique to Evaluate Soil and Water Resources Degradation

In addition to the evaluation of soil redistribution by FRN at the study site, the discrimination of sediment contribution from different sources is relevant for understanding sediment transport and distribution processes at mixing points. (Hirave et al., 2023b, 2023c; Huang et al., 2020). The sediment FP technique has been successfully applied to quantify the contribution of mobilized sediment in catchments (Bravo-Linares et al., 2018; Brandt et al., 2018a; Mabit et al., 2018; Gaspar et al., 2019a)). To evaluate the source of suspended sediments using unmixing models, different tracers have been evaluated for the FP technique: color, magnetism, geochemistry, stable isotopes such as CSSI (Bravo-Linares et al., 2018; Brandt et al., 2018a; Mabit et al., 2018; Peralta et al., 2020), and the use of a variety of other tracers, such as biomarkers (Gaspar et al., 2019a).

The main assumption underlying the FP technique is the direct comparison between tracer properties in sediment mixtures and in the source's sediment. (Lizaga et al., 2020). Several unmixing models have been developed: ISOSOURCE, SIAR, CSSIAR, MIXSIAR, and FINGERPRO (Phillips et al., 2003; Stock et al., 2013; de los Santos-Villalobos et al., 2017; Lizaga Ivan et al., 2020a, 2020b; Gaspar et al., 2019c; Gaspar et al., 2022; Borges et al., 2021) using different approaches (frequentist, bayesian, etc.). The objective of these models is to quantify the proportion of sediment from different sources in sediment mixtures. The technique has been applied to explore variations in source contribution and sediment origin during floods, as well as extreme precipitation events, which are important factors in landscape change. (Gaspar et al., 2019a, Lizaga et al., 2019). It has also been combined with remote sensing to evaluate the transport of suspended sediments and associated elements induced by rainfall and the agricultural cycle. (Lizaga et al., 2020a). Several tracers, such as geochemical elements and other soil properties (radionuclides, soil sizes, etc.), have been included in the FP application to improve the discrimination capacity (Lizaga et al., 2020a, 2020c). Recently, a new approach has been developed to incorporate CSSI (isotope ratio) data together with geochemical elements (scalar) as tracers in the FP technique (Lizaga et al., 2022b; Lizaga et al., 2024). Associated

with the relevance of the correct selection of tracers in FP techniques, a new consistency analysis method was applied in several landscapes to identify erroneous tracers (Borja et al., 2021; Navas et al., 2020; Lizaga et al., 2021; Navas et al., 2022).

CSSI included as tracers in the FP technique have demonstrated a high level of discrimination for assessing the proportions of sediments from different types of land use as sources. (Brandt et al., 2018a; Mabit et al., 2018; Gibbs et al., 2020). For this reason, the development of its application to define sediment contributions in dissimilar basins around the world is more detailed. The CSSI tracer, based on the measurement of $\delta^{13}C$ signatures of organic biomarker compounds such as fatty acids (FAs), has been used since the late 2000s to strengthen the understanding of sediment production and balance in various ecosystems. (Mabit et al., 2020). CSSI emerged as a useful technique to track the origin and fate of eroded soils in the landscape and to distinguish between land use types, including forested watersheds (Mabit, 2018a, 2018b; Bravo-Linares et al., 2018, 2019; Brandt et al., 2018b); although the accuracy and precision of tracer selection procedures for unmixed sediment sources is an area that needs to be investigated in relation to sediment FP **(**Huangfu, 2020**).**

The novel CSSI technique was introduced in 2008, in Ireland, to study the origin of sediments in estuaries (Mabit L., et al., 2018a; IAEA-TECDOC-1881, 2019), and was introduced in Latin America and the Caribbean in 2014. (Peralta et al., 2020). The method can be applied to several biomarkers **(**FAs**,** n-alkanes, etc.) and different isotopes ($\delta^{13}C$ and/or $\delta^{2}H$), being valid to reconstruct changes in the contributions of land use sources from sedimentary records, correcting isotopic values of $\delta^{13}C$ (Bravo-Linares et al., 2018; Brandt et al., 2018a; Mabit et al., 2018). Torres (2019) combined two nuclear techniques: FRN to document soil redistribution and CSSI to identify sediment sources in central Argentina. Mabit et al., (2020) used the soil organic biomarkers for tracing the origin of eroded sediment in Petzenkirchen (Austria). The $\delta^{13}C$ of saturated long chain FAs (i.e., C24:0 and C26:0) allowed the best discrimination to establish the contribution of sources to sediment collected at the watershed outlet, confirming that information with δ C-FAs analysis could provide unique support to enable effective agroecosystems management. The CSSI technique enables the identification of soil erosion sources and deposition sites through the analysis of the isotopic signature ($\delta^{13}C$) of long-chain **FAs** (Hirave, 2020a). It is not a quantitative technique, so it is recommended to combine it with other sediment load estimation techniques. Knowledge of the sources of soil erosion provides the necessary information to take preventive measures to preserve this natural resource and mitigate the negative ex situ effects. In this way, joint efforts can be made to improve soil fertility and, consequently, provide ecosystem services (Marisol et al., 2020).

The CSSI technique is widely used around the world, one can mention the work developed by Li et al. (2021), to understand sedimentation and track soil organic carbon and nitrogen sources in highly eroded mountain watersheds controlled by a dam; the results provided scientific insights to develop effective management practices for soil erosion and nutrient loss control in highly eroded agricultural watersheds. Winterová, et al., 2022, modeled water erosion and sediment transport in a reservoir with WaTEM/SEDEM software; their results supported the idea that the introduction of green areas within farmland is beneficial to the landscape and allows for reduced soil erosion and reservoir sedimentation. This idea is corroborated in the research developed by Atwell et al. (2022), where they demonstrate the effect of agricultural intensity on the contribution of nutrients and sediments in hydrographic basins, e. g., the absence of green areas makes the landscape vulnerable to degradation due to water erosion.

These statements are further confirmed by Daramola et al., (2022), where land use is shown to be the most dominant factor in land degradation. The impacts of the land use change, associated with the area of this change and runoff on the sediment production of the watershed, are evaluated. Initially it was proposed that an uncontrolled flow of sediment destabilizes a dam, and the sediments produced are influenced by the predominant types of land use and land cover, along with the amount and intensity of precipitation. Subsequently, results obtained using the Soil and Water Assessment (SWAT) software, affirmed that land use types exerted a more dominant control over runoff and sediment production than land cover areas, without ruling out climatic influence.

In the authors' experience, land use is a very important parameter in soil and water degradation assessments. The authors also support the idea that soil cover is important and cannot be downplayed as a crucial conservation measure to minimize the effects of water erosion, confirming the ideas of Winterová et al. (2022) who state that soil cover reduces soil degradation and the consequent loss of water quality. Land use and soil cover are very important aspects that must always be valued with equal priority.

Recent research by Belayneh et al., (2023) evaluated the impact of land use/cover change on the dynamics of soil loss and sediment export, particularly in fragile mountain river basins. The Random Forest classifier in the Google Earth Engine platform was employed for land use/cover classification, and the Integrated Valuation Ecosystem Services and Trade-offs (InVEST) Sediment Delivery Ratio model was used for soil loss and sediment export modeling. Iván et al. (2018) corroborated the above, in a work conducted to evaluate the effect of land use/cover changes over decades on the hydrological network of a watershed in northeastern Spain. They confirmed that information on the spatial distribution of land use/cover is essential to monitor runoff response as the main cause of water erosion and to analyze watershed hydrology. Jazmín (2022) shown the influence of land cover by suggesting that the hydrological regimes of the Brazilian and Paraguayan drainage areas of the Paraguay River basin were altered because of changes in the vegetation cover of the basin, as a direct result of the development of productive activities and the unplanned expansion of urban and rural populations. Research conducted by Marchesini et al. (2020), in the South American region of Chaco, demonstrated the impact of raindrops on bare soil as the first stage of erosive processes, increasing the vulnerability of the soil when it has no vegetation cover to assimilate the mass and kinetic velocity that determines the erosivity of raindrops. The work of Yanjun et al. (2020), also studied the subject by evaluating the effect of rain splash on soil particle transport using a modified model to study short slopes in China. They found that the number of splashed particles decreases exponentially with increasing distance, and the maximum splash distance is affected by the kinetic energy of rain. In addition, they found that covered soil decreases the kinetic energy of the raindrop, slowing degradation in the landscape.

Another feature of the CSSI technique is shown in the work of Gibbs et al. (2020), where it is confirmed that submarine canyons provide a vector for organic carbon transport to the deep ocean and that organic matter in the canyon sediments has strong terrigenous affinities throughout the sedimentary system. The study adds to the growing evidence that the fingerprint of human activities on land extends well beyond the coast and continental shelf through the transport of sediment and associated materials (including potential contaminants) via a variety of pathways, including canyon transport (Kane and Clare, 2019). The depletion distance and transport mechanisms of turbidity currents carrying terrestrial materials offshore through submarine canyons are likely to be reduced by the incorporation of organic matter, which favors burial and preservation of organic carbon. (Craig et al., 2020).

The recent work of Hirave et al. (2023b, 2023c), exposed the need for isotopic fingerprinting of sediment sources based on land use, given rapidly changing land use patterns and frequent weathering events.

Extreme conditions lead to increased sediment flux into freshwater systems worldwide. It states that the application of variability of hydrogen isotopic compositions (δ^2H values) of specific biomarkers of vegetation and soil sediments is relatively underexplored to identify sources of freshwater suspended sediments as a function of land use, and demonstrates that its use provides new insights and allows complementing the information obtained by carbon isotopic analysis.

Another recent research by Peralta et al. (2023) demonstrates the value of the CSSI technique as a tool to assess sediment contributions associated with different land use changes within the Panama Canal watershed. The influence of potential sediment inputs was evaluated, and the main land use contributions to Lake Alhajuela were defined.

2.3. The IH Technique to Evaluate Soil and Water Resources Degradation

Water resources management requires a comprehensive understanding of the interactions between the components of the water cycle, with the study of dynamic water systems requiring approaches capable of capturing processes across multiple spatial and temporal scales**.** The Global Precipitation Isotope Network is a global network for monitoring hydrogen and oxygen isotopes in precipitation that operates with the cooperation of numerous partner institutions in IAEA Member States (IAEA, 2019)**.** Water resources are the environmental element most vulnerable to the direct impacts of mining, as they are the most polluting anthropogenic sources. (Santana et al., 2020; Kumar et al., 2021). Industrial effluents pose a serious threat to aquatic biota and ecosystems, with textile waste being the most harmful pollutant. Municipal and industrial wastewater contains polluting chemicals that reduce water quality. (Chen et al., 2020). The most widespread types of contaminants in water are heavy metals, organically bound metals and metalloids, organic species, polychlorinated biphenyls, pesticides, detergents and chemical carcinogens (Nunes and Malmlof, 2018). These pollutants make the environment so inhospitable that species are no longer able to thrive (Ameta, 2018), thus destroying the environmental sustainability of water resources (Le Ba, 2020).

Hydrological information is essential for measuring water availability and exploring the nature of its problems and conflicts (Bicalho et al., 2019), supporting the sustainable development of water resources through their efficient management as a source of water supply to meet needs in an equitable manner while maintaining their quality. For this purpose, techniques such as water recycling are carried out, but there are other types of tools such as isotopic and nuclear techniques (Amiri et al., 2019). The results of their application support governmental decision makers in policy formulation for strategic planning and management of water resources (IAEA Bulletin, 2019a, 2019b). Isotopic investigation of precipitation, surface water and groundwater is necessary for sustainable management of water resources and for understanding the present climate and its past and future variations. (Valdivieso et al., 2021).

The analysis of temporal and spatial variations of isotopes in precipitation, mainly oxygen-18 (^{18}O) and deuterium (^{2}H), provides basic data in the IH technique applied to the inventory, planning and development of water resources. The use of the IH technique in the identification of groundwater sources is one of the latest scientific technologies used, with isotopes of oxygen, hydrogen, carbon and nitrogen being the most utilized (Saleh and Hassan, 2021). Its many applications include analysis of groundwater recharge from both precipitation and irrigation water; determination of the frequency, rate, and origins of recharge; groundwater flow pathways, including deep-circulating mineral waters; groundwater mixing; paleosurface water origins; groundwater discharge through evaporation and surface water; modeling of dynamic tropical river inflows; submarine groundwater discharge and groundwater salinity, among others (Tweed et al., 2020).

Stable isotopes in water are widely applied in studies of river hydrological processes. Isotopic enrichment occurring along the flow direction is used as an indicator to estimate evaporation from the river surface (Chen and Tian, 2021). These isotopic techniques provide essential information to develop strategies that improve water use efficiency in agriculture, providing solutions to mitigate growing water scarcity (Serres et al., 2019).

Agricultural production and food security depend on water availability (Sharpley, 2018), thus improving its management and quality is essential for a productive and sustainable agriculture. Accurate measurement and evaluation of the spatial and temporal dynamics of soil water content is a crucial first step in addressing water management problems. The isotopic variation of water (^{18}O and ^{2}H) in the water vapor surrounding plants allows the separation of the evapotranspiration process into the individual components of plant transpiration and soil evaporation, thus minimizing evaporation and improving water use efficiency in agriculture (Langridge and Fencl, 2020). Stable isotopes in water (^{18}O and ^{2}H) are suitable for assessing groundwater sources and quantifying their recharge rates, as each source has a unique and constant isotopic composition (if it does not change phase in flow) (Kpegli et al., 2018). Stable and radioactive isotopes provide relevant information on the age of groundwater and its flow direction, as well as the recharge and discharge zones of the aquifer. In addition, isotopic, piezometric and geological data are used to build conceptual models of

groundwater flow. Natural variation in stable isotope ratios of water is a tool for measuring and partitioning water fluxes between different systems (Enalou et al., 2018).

2.3.1. Application of IH as a Scientific-Technical Tool to Support the Sustainability of Water Resources

A detailed analysis of the use of IH allowed to identify some characteristics of the techniques applied, the radionuclides used, and the main representative scopes implemented in these studies. From the review of 25 recent articles on the application of IH in different parts of the world, the main isotopes used in the studies are the traditional water isotopes (18O and 2H), which are included in all studies to evaluate water dynamics. The review of these studies shows that isotope hydrology techniques are an important source of information on hydrological processes and directly support the improvement of water resources management. The results of all the studies presented demonstrate the effectiveness of using water isotopes as a relevant tool for characterizing and assessing water dynamics in order to support its sustainable management. Additional radioactive isotopes were incorporated as supported in the IH applications: 3H (Shi Peijunet et al., 2021; Shi Dongping et al., 2021), δ15N (Jung et al., 2021), 222Rn (Yang et al., 2021; Shi Dongping et al., 2021), δ37Cl and δ13C (Bagheri, et al., 2021), 14C (Zhao et al., 2018), and the stable Carbon applied in a paper (Mathwich et al., 2019). The reviewed research using IH covers several areas. The most common is the characterization and investigation of groundwater sustainability (Rajaomahefasoa et al., 2019; Li et al., 2019; Bedaso et al., 2020; Sileo et al., 2020; Avellano et al., 2020; Xiang et al., 2020; Mahlangu et al., 2020; Chen and Tian, 2021; Dar Farooq et al., 2021; Shi Peijun et al., 2021). Some studies are related to the assessment of human disturbance (Zhao et al., 2018; Zhu et al., 2021; Jung et al., 2021) and the assessment of human risk exposure through ingestion (Enalou et al., 2018). There are papers focused on supporting archaeological studies (Mathwich et al., 2019), characterizing geothermal resources (Sasaki et al., 2021) and improving hydrological modelling (Jafari et al., 2021). Other contributions focused on the study of atmospheric processes and moisture contribution at the regional scale (Sánchez-Murillo, et al., 2023) and the assessment of water behavior absorption depths in tropical forests (Sohel et al., 2021). In terms of the location of IH study sites, Asia is the most represented region, with works from China, Japan, South Korea, India and Australia (Zhao et al., 2018; Li et al., 2019; Xiang et al., 2020; Sasaki et al., 2021; Chen and Tian, 2021; Zhu et al., 2021; Dar Farooq. et al., 2021; Shi Peijun et al., 2021; Shi Dongping et al., 2021; Yang et al., 2021; Jung et al., 2021; Sohel et al., 2021). There are also contributions from Africa: Ethiopia and Magadascar (Rajaomahefasoa et al., 2019; Bedaso et al., 2020; Mahlangu et al., 2020); from the Middle East: Iran (Enalou et al., 2018; Heydarizad et al., 2021; Jafari et al., 2021; Bagheri et al., 2021); from Europe: Spain and Croatia (Mathwich, 2019; Mance et al., 2022); and from Latin America: Mexico and Argentina (Avellano et al., 2020; Sánchez-Murillo et al., 2023; Sileo, et al., 2020; Calvi et al., 2022).

3. Analysis of Trends in the Use of Isotopic and Nuclear Techniques in Water and Land Degradation Research

A traditional literature review was conducted to gain the most comprehensive understanding of the current state of isotopic and nuclear techniques and to propose a hypothesis that integrates the synergistic convergence of these techniques to evaluate soil degradation.

The investigative works conducted by various specialists encompass a range of topics related to soil and water degradation. Additionally, they include an assessment of the feasibility of utilizing isotopic and nuclear techniques for characterizing and evaluating the impacts of these degradations. Collectively, these works have been referenced and comprise a total of 138 papers. Of the total number of publications, 20 introduce the importance of the application of nuclear and isotopic techniques, demonstrating their utility in assessing the degradation of natural resources, namely water and soil. The remaining 118 papers pertain to the advancement of these techniques.

The selection of research works was based on the timeliness of their completion. To this end, a comprehensive search for relevant scientific papers was conducted across a range of databases, including the Web of Science, Scopus, the Scientific Electronic Library Online (SciELO),

ResearchGate, Google Scholar, and others. The search for current studies covered the period 2018–2024 and was limited to Spanish (4 papers) and English language (135 papers). The objective was to establish research trends by reviewing publications on the way in which researchers approach assessments of the degradation of soil and water sources through the application of three nuclear and isotope techniques: FRN, FP and IH, and related research published in high-impact journals at a global level. The search terms (keywords) were associated with the use of nuclear and isotopic techniques, as well as environmental phenomena in the landscape. This included isotope hydrology, ^{18}O, ^{2}H (deuterium), fallout radionuclide, ^{137}Cs, ^{210}Pb, ^{7}Be, FP, CSSI, water erosion, integration, sedimentation, land degradation, and other relevant factors.

The search and selection of the analyzed publications were always dedicated to obtaining the greatest representation of the research developed in recent years and covering a wide range of technical and geographical scenarios. This was done to address the detailed analysis of the current trends in the use of the nuclear techniques. A total of 119 papers are summarized in Table 1, which shows the distribution of the three techniques analyzed (FRN, FP and IH) according to the development of their application and their integrative link with other techniques.

Table 1. Integration of isotopic and nuclear techniques and the universal equation.

Nuclear techniques	FRN	FP	IH	Integration FRN/FP/IH	Universal equations	Total papers
FRN	23	1	1			25
FP (CSSI)	4	36				40
IH			42			42
Integration FRN/FP/IH				2		2
Universal equations	3				7	10
Total paper/techniques	30	37	43	2	7	119

In light of the fact that erosion and sedimentation phenomena are intricate processes occurring in the landscape that result in the degradation of both soil and water resources, there is a clear necessity for the integrated or combined use of the techniques that have been analyzed in order to gain a deeper understanding of these phenomena and to contribute to the development of integrated solutions that will help to minimize these degradations. As evidenced in Table 1, the application of nuclear techniques is notably limited, with individual techniques being predominantly utilized. These techniques are employed with the objective of characterizing and addressing specific forms of degradation, whether soil-related or water-related. A mere five research papers demonstrate the joint utilization of the FRN and FP techniques (with CSSI employed as a tracer); a single paper illustrates the combination of FRN and IH; and just two papers exhibit the comprehensive integration of the three techniques under examination (FRN, FP and IH). The use of the universal soil loss equation is also examined, with particular attention paid to the necessary modifications that must be made in order to ensure the fulfillment of current requirements regarding the results that are produced. The review confirms that the universal equations continue to be applicable on a global scale, and three papers demonstrate the use of these equations in combination with the FRN (utilizing the ^{137}Cs tracer to assess the redistribution of soil in the landscape). Figure 1 depicts the timelines of the selected research works, which were conducted entirely within the period spanning 2017 to 2024. These works are collectively focused on the topic of soil and water degradation and the development of three isotopic and nuclear techniques that are instrumental in assessing the sustainable development of these resources. A total of 139 papers are referenced, of which one was published in 2017, 13 in 2018, 22 in 2019, and 30 in 2020. In addition, there were 30 works published in 2021, 23 in 2022, 20 in 2023, and one in 2024.
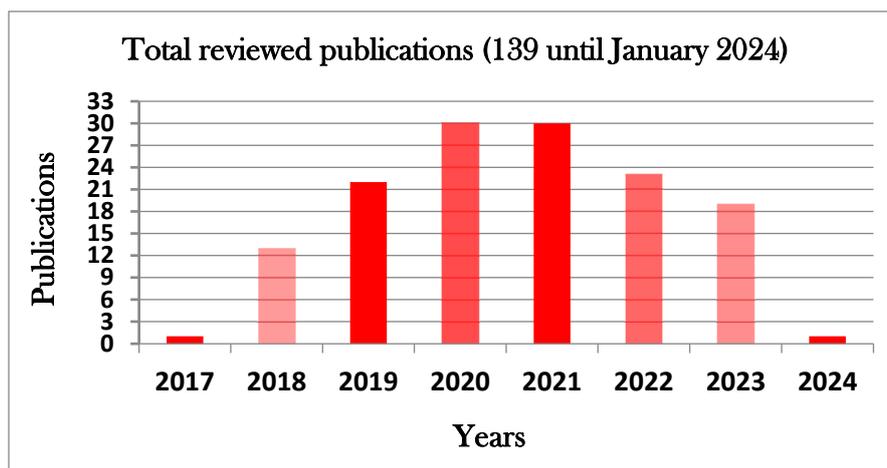
Figure 1. Reviewed publications for the selected period (2018-2024).

3.1. Trends and Perspectives in the Isotopic and Nuclear Techniques Application in the Soil and Water Degradation Assessment

The specific characteristics of each nuclear technique are evident in their individual application as scientific-technical tools for the characterization and evaluation of environmental variables, namely water, soil and sediment. They contribute to the resolution of particular, well-defined problems. Since their inception, the particular use of these techniques without integration has been a pervasive trend worldwide for addressing environmental issues related to water, soil, and sediment. Degrading phenomena and their underlying causes have been examined as standalone occurrences without considering the potential for interconnections that could impact multiple environmental variables. The application of these isotopic and nuclear techniques has not been linked to the possible analysis of a sequential process in which one degradation could potentially lead to another. The integrated application of the nuclear techniques evaluated in this work would substantially improve the existing deficiencies in the use of tools capable of addressing the effects of climate change and problems regarding the sustainability of land and water conservation. This justifies the search for methodologies capable of proving comprehensive solutions to the problem expressed in the dissimilar national programmes that address the issue in countries around the world (Peralta et al., 2000). The intricate nature of erosion and sedimentation processes, which are responsible for soil and water degradation, necessitates their comprehensive characterization and evaluation. This approach enables the identification of the underlying causes and the implementation of effective mitigation strategies and sustainable management practices. In the particular case of the Latin American and Caribbean, various investigations have been carried out in the framework of four international projects, such as RLA5051 (2009-2013), RLA 5064 (2014-2016), RLA 5076 (2018-2021) and CUB 5024 (2022-2024), as well as the development of similar national cases in different countries such as Argentina, Bolivia, Brazil, Chile, Colombia, Cuba, Guatemala, Haiti, Honduras, Mexico, Nicaragua, Panama, Paraguay, Peru, Dominican Republic, Uruguay and Venezuela. In the last decade, conditions have been created for the change of paradigms and the beginning of the integrated use of isotopic and nuclear techniques (FRN, FP-CSSI and IH) in sequential order to obtain more comprehensive solutions to problems linked to the sustainability and degradation of terrestrial and aquatic ecosystems (Brandt et al., 2018 (b); Peralta et al., 2020).

The three isotopic and nuclear techniques analyzed offer valuable scientific and technical advantages in terms of the results they produce in a range of applications. However, in order to fully leverage these potentialities and achieve optimal effectiveness, their integrated use is proposed. This approach is based on the premise of evaluating the phenomena as processes occurring in the landscape. Furthermore, it suggests a possible use of the synergic convergence of the results obtained and their application in a sequential order. The integration of these techniques allows for the characterization and evaluation of this process, thereby addressing the uncertainties associated with

its stages. The redistribution of soil can be attributed to its degradation by water erosion. This process can be analyzed with FRN techniques. Subsequently, the degraded soil is transported and finally accumulated in the landscape and surface water bodies. The origin of the accumulated soil can be analyzed with CSSI techniques, while the dynamics of the water resources in the study area can be characterized with IH techniques.

3.2. Case Study

To demonstrate the feasibility of the hypothesis established in this review work, a synthesized example of results obtained in a real case study is presented.

An important hydrographic basin situated in the central region of Cuba was examined in order to demonstrate the implementation of an integration methodology combining isotopic and nuclear techniques (FRN, FP and IH) for the purpose of evaluating the degradation of land and water resources. In the province of Cienfuegos, within the Hanabanilla hydrographic sub-basin (176.47 km^2), two sub-basin sectors were selected for the application of isotopic and nuclear techniques: the "River Hanabanilla" sector (66.11 km^2) and the "River Charco Azul" sector (47.67 km^2). The region is distinguished by the presence of the Hanabanilla reservoir, which is home to a hydroelectric generation plant. The area comprises sectors with topography characteristic of mountainous regions, featuring elevated slopes and considerable runoff and water erosion. The study area's predominant land uses are forestry, protected areas, coffee crops, temporary crops, livestock, and human settlements (Figure 2).
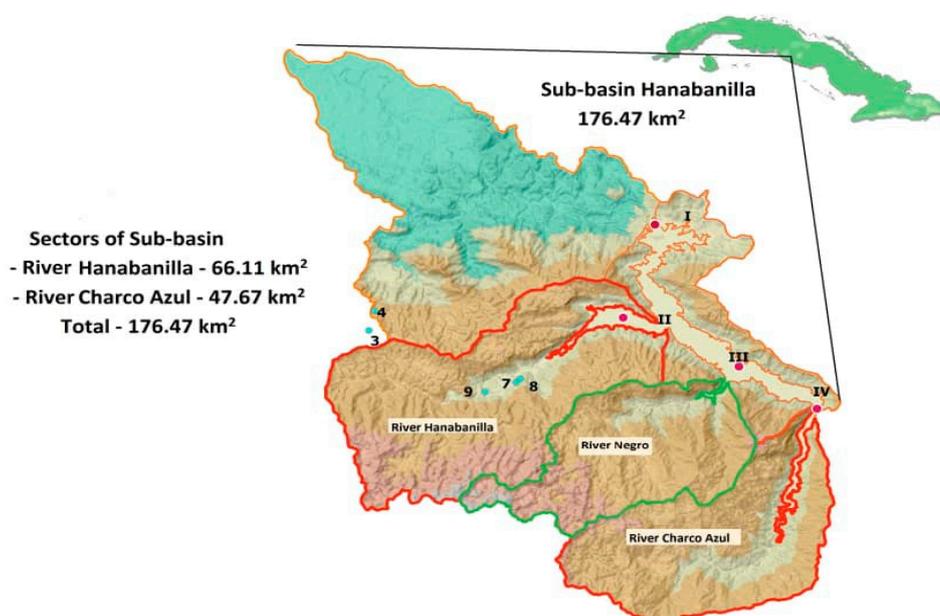

Figure 2. Hanabanilla sub-basin and selected sectors in the case study.

The proposed working hypothesis is that the integration of isotopic and nuclear techniques facilitates the design and implementation of a sampling strategy (in terms of sediment sources and mixtures), supports the interpretation of results, allows for the quantification of degradation, the identification of causes and sources of degradation, and the assessment of water resource dynamics.

These outcomes are supported by the results obtained from techniques applied in previous stages.

A range isotopic and nuclear techniques were employed, including FRN (^{137}Cs), FP (CSSI), IH (^{18}O and ^{2}H) and geochemistry of water. A total of 56 samples were analyzed for FRN, 25 for FP and 14 points for periodic IH sampling, including 4 sediment cores taken at the bottom of the Hanabanilla reservoir (points I, II, III and IV). The initial technique, FRN, was implemented in both sectors with the objective of evaluating the redistribution of soil. The results obtained from this technique were then taken into account during the sampling design and the selection of source and mixture points

in the landscape. Sequentially, the quantification of the final contributions of the sediments was obtained using FP. Finally, the third technique, IH, was employed together with FP to assess the impact of water dynamics (underground, superficial and reservoir) on the existing sedimentation zones in the Hanabanilla river sector and the sub-basins as a whole.

To test the proposed hypothesis, the FP technique was applied in the two selected sectors in two different ways. Initially, the FP results were obtained without considering the results of the FRN technique. Subsequently, the FP results were obtained using the FRN soil redistribution data to reinforce the selection of source soil and mixture sediment zones, which represents a fundamental stage of the FP technique. The results were evaluated using a range of statistical techniques, including range test, principal components analysis (PCA), goodness of fit of the solution, source contribution graphs, and others, to estimate the relevance of the two application variants with or without integration of FRN data.

In the case of the River Hanabanilla sector, three sources were considered in developing the FP technique: forestry, temporary crops, and coffee crops. Additionally, one mixing zone was identified. The tracer utilized was CSSI (carbon chain 14C to 34C), and the FingerPro model (Lizaga et al., 2020) was employed for estimation of sediment contributions. The results obtained are show in Table 2.

Table 2. Results of the FingerPro runs for the case of the River Hanabanilla sector.

FP analysis details	Integrated techniques	Not integrated techniques
	Results	
PCA test	78% explained variability	66 % explained variability
Range test	Removed 9 tracers	Removed 5 tracers
Goodness of fit	91%	70%
Additional sampling points according criteria (+/-)	Included 2 new points in the analysis (1 source, 1 mixture)	-
Estimated contributions (sources)	50% Forest 40% temporary crops 10% Coffee crops	80% Forest 15% temporary crops 5% Coffee crops

In the case of the River Charco Azul sector, three sources were considered during the application of the FP technique: forestry, coffee crops, and fruit trees. Additionally, one mixing area was incorporated into the analysis. The tracer utilized was CSSI (carbon chain 14C to 34C), and the FingerPro model, as previously described (Lizaga et al., 2020), was employed for the assessment of sediment contributions.

Integration of the PCA test with the FRN technique enables estimation of the source contributions of the three sources under consideration. Without integration with FRN, determination of the source contributions is challenging due to the presence of multiple peaks in the distribution. Exclusion of the fruit tree source contributions facilitates identification of the source contributions. The results are presented in Table 3.

Table 3. Results of the FingerPro runs for the case of the River Charco Azul sector.

FP analysis details	Integrated techniques	Not integrated techniques
	Results	
PCA test	60% explained variability	58 % explained variability
Range test	Removed 1 tracer	Removed 1 tracer
Goodness of fit	86%	70%
Additional sampling points according criteria (+/-)	Included 2 ne w points in the analysis (1 source, 1 mixture)	-
Estimated contributions (sources)	50% Forest 40% temporary crops 10% Coffee crops	90% Forest 10% Coffee crops Temporary crops are no included

The IH technique, which is associated with the study of the dynamics of surface and underground waters, was applied in the River Hanabanilla sector with periodic measurements of precipitation, wells, springs, and the reservoir waters. Isotopic measurements of ^{18}O and ^2H were conducted, and geochemical parameters of the water were analyzed as well, allowing the local isotopic line to be obtained. This process also enabled the identification of phenomena (such as evaporation) that deviate the isotopic behavior of the local line. The isotopic and geochemical data were collected using the FP technique to analyze the water contributions within the reservoir across the three primary basin sectors within the sub-basin Hanabanilla (River Hanabanilla: point II, River Negro: point III, and Charco Azul: point IV). The sources were identified at the discharge point of each sector, and the mixing was taken at the outlet of the reservoir (point I) (Figure 3).
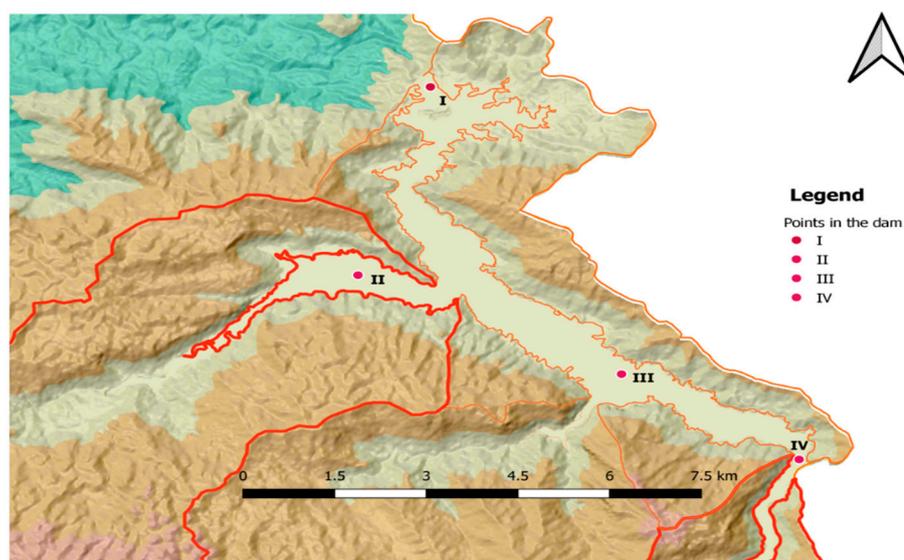

Figure 3. Selected points in the Hanabanilla Reservoir to evaluate water discharge contributions.

The Lineal Discriminant Analysis (LDA) of the initial data shows significant differences between the evaluated sources (II, III and IV), validating their use for the FP technique. Point I coincides with the point of discharge of the waters in the dam (coincident with the core I taken at the bottom); this point is the place where all the waters arrive with their mixtures (final mixture). The final source contributions identify the River Negro sector as the most important source with 78%, followed by the River Charco Azul with 15% and finally the River Hanabanilla with 7%. These results are correlated with sedimentation dating studies carried out in the Hanabanilla reservoir, which also showed the mouth of the River Negro sector as the source of the greatest contribution of sediments to the reservoir (Misael et al., 2017).

The integration of the results with this third technique (HI) facilitated a more accurate identification of significant differences between the evaluated sources, enabling their differentiation and providing substantial support for the identification study of sediment contributions (as demonstrated by the FingerPro model through the discriminant analysis conducted on the selected tracers in the investigation). The integrated application of isotopic and nuclear techniques also permitted the incorporation of the FP technique into the hydrogeological study of the case study for the analysis of mixtures. The water contributions within the River Hanabanilla sector were analyzed from five wells (3, 4, 7, 8, 9) as potential sources. The mixing point was taken at the discharge point of sector II, and a similar tracer was used as in the previous analysis (chemical macro-components, isotopes, and physical-chemical), as illustrated in Figure 4.
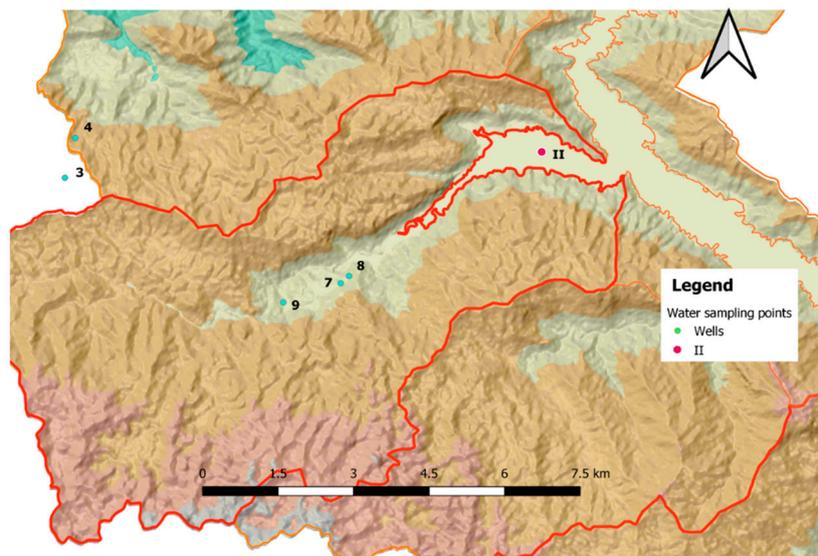
Figure 4. Water sampling points (wells) selected in the sector of sub-basin River Hanabanilla.

In the initial data evaluation, the range test excluded two tracers (total dissolved solids and electric conductivity) as suitable for inclusion in the study. The LDA revealed notable distinctions between the evaluated sources and identified partial overlap for wells 7 and 8. The distinct contributions associated with groundwater at the discharge point of the Hanabanilla sector have been identified. The wells with the highest contribution, which approaches 75%, are wells 3 and 4 (which are situated more than 9 km away) and well 9, which accounts for 25%.

The integrated application of isotopic and nuclear techniques (FRN, FP, HI), developed in this study case, enabled a comparison of results, thus identifying the limitations of their individual use and the significant potential of the results provided with their use in an integrated manner (see Figure 5). The analysis of soil and water degradation phenomena must consider the various aspects associated with soil redistribution, sedimentation processes, and their relationship with water dynamics. The integrated use of these techniques can significantly enhance the characterization of water and land degradation phenomena, the evaluation of their impacts, and the formulation of strategies for the sustainable management of water and land.

Figure 5. Summary of results with the integrated application of isotopic and nuclear techniques.

4. Conclusions

In light of the complex nature of erosion and sedimentation processes in landscapes and water reservoirs, it is crucial to conduct a comprehensive characterization and evaluation of these phenomena. This approach facilitates the identification of the underlying causes and the implementation of sustainable management strategies. However, the use of individual nuclear techniques often yields only partial results, which constrains the ability of decision-makers to develop optimal environmental management strategies.

The integrated application of isotopic and nuclear techniques, developed in the study case, permitted a comparison of results, thereby enabling the identification of the limitations of their individual use and the significant potential of the results provided with their use in an integrated manner.

There is no evidence that an integrative methodology was employed in the application of these isotopic and nuclear techniques, which do not facilitate the analysis of the sequential process in which degradations of the soil and water could potentially occur one after the other.

The findings of research conducted in international projects, both completed and ongoing, directed by the authors and funded by the IAEA, illustrate a significant shift in the utilization of isotopic and nuclear techniques (FRN, FP, and IH). These outcomes highlight the efficacy of their integrated application in a sequential manner for the assessment of degradation processes in the landscape.

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