



Sediment characteristics affecting natural radionuclide distribution and radiological assessment in a tropical wetland near Maanshan Nuclear Power Plant, Southern Taiwan

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Abstract This study establishes a crucial post-operational radiological baseline for the Lungluan Wetland (LLW), a critical ecosystem near the Maanshan Nuclear Power Plant (NPP) in Taiwan, ahead of its 2025 decommissioning. Analysis of fifty sediment samples confirmed the absence of anthropogenic contamination (no detectable ^{137}Cs). The activities of natural radionuclides were comparable to global medians for ^{40}K (range: 125.7–652.3 Bq/kg) and ^{232}Th (9.9–58.7 Bq/kg), while ^{226}Ra (7.9–33.4 Bq/kg) was lower than the Asian wetland median. Although all radiological hazard indices were well below safety limits, the spatial distribution of radionuclides was highly heterogeneous. Higher concentrations were strongly correlated with fine-grained sediments (clay)

and high organic matter content, predominantly in low-velocity depositional zones. These findings demonstrate that sediment characteristics and wetland hydrodynamics are the primary drivers of radionuclide distribution. This research provides an essential benchmark for assessing environmental changes during the NPP decommissioning and shows that sediment properties can serve as effective indicators for identifying potential accumulation hotspots, thereby optimizing future monitoring strategies.

Keywords Natural radionuclides · Sediment characteristics · Radiological assessment · Tropical wetland · Nuclear power plant

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Introduction

Human radiation exposure is significantly influenced by naturally occurring radioactive materials (NORMs) present in the environment (Afzal et al., 2022; Khan et al., 2023). These radionuclides, primarily originating from primordial sources like uranium-238 (^{238}U), thorium-232 (^{232}Th), and potassium-40 (^{40}K), contribute approximately 87% of the total radiation dose received by humans (Aközcan et al., 2018; Ugbede, 2020). Long-term exposure can lead to severe health consequences, including chronic respiratory diseases and various malignancies through cellular damage and oxidative stress (Betlazar et al., 2016; Einor et al., 2016; Kamiya et al., 2015; Talapko et al., 2024).

In aquatic ecosystems, sediments serve as reliable long-term indicators of radioactive contamination, acting as both sinks and transport media for radionuclides (Appleby et al., 2001; El-Reefy et al., 2010; Ruiz-Fernández et al., 2022). The distribution and concentration of radionuclides within sediments are influenced by multiple factors, primarily grain size distribution, mineralogical composition, and organic matter content. Studies have consistently shown that fine-grained sediments ($<63\ \mu\text{m}$), rich in clay and silt, exhibit higher radionuclide activities due to their larger specific surface area and greater adsorption capacity (Madruga et al., 2014; Navas et al., 2011). Similarly, organic matter enhances radionuclide retention through complexation and adsorption, showing strong positive correlations with radionuclide concentrations (Navas et al., 2011; Ren et al., 2024). In lentic ecosystems like wetlands, low-flow velocities facilitate the deposition of these fine-grained, organic-rich particles, creating potential hotspots for radionuclide accumulation.

In wetland environments, Zare et al. (2016), using high-resolution gamma-ray spectrometry, found varying activities in Anzali international wetland sediments: 371.9–652.3 Bq/kg for ^{40}K , 17.6–45.8 Bq/kg for ^{232}Th , 18.1–33.4 Bq/kg for ^{226}Ra , and lower levels for ^{235}U and ^{137}Cs . The importance of sediment characteristics in element distribution has been further evidenced in closed lake systems, where Ren et al. (2024) demonstrated that suspended particulates and sediments act as significant reservoirs for organic matter through various physical and chemical processes. However, comparative research on

radionuclide distribution patterns across different aquatic systems remains relatively limited.

Activity ratios between different radionuclides, particularly $^{40}\text{K}/^{226}\text{Ra}$, $^{40}\text{K}/^{232}\text{Th}$, and $^{232}\text{Th}/^{226}\text{Ra}$, can provide valuable insights into geochemical processes and potential contamination in sedimentary environments (Harikrishnan et al., 2018; Ugbede et al., 2020; Caridi et al., 2021). These ratios offer important information about sediment dynamics and the behavior of radionuclides under varying environmental conditions. El-Reefy et al. (2010) investigated the distribution of radionuclides in lake sediments and found relationships between radionuclide activities and sediment characteristics, including particle size distribution and organic matter content. Their study, along with others, suggested that sediment properties play important roles in controlling radionuclide distributions and their relative abundances in aquatic environments.

The relationship between sediment characteristics and radionuclide distributions has been well documented by Khan et al. (2023), who found significant correlations between physicochemical properties of sediments and radionuclide activities in Chashma Lake sediments. While Darwish et al. (2013) focused on radiological hazard assessment in lake environments, their study also provided insights into the relationship between sediment properties and radionuclide distributions. These findings, along with studies by El-Reef et al. (2010) and Sirin et al. (2019), demonstrate that radionuclide distributions and their relationships with sediment characteristics can serve as valuable tools for understanding geochemical processes and environmental conditions in aquatic systems.

Previous studies have examined the distribution of radionuclides in various aquatic environments, including wetlands (Zare et al., 2016), lakes (Afzal et al., 2022; Khan et al., 2023; Ogundele et al., 2018), and river systems (Lu et al., 2008; Zorer et al., 2019; Caridi et al., 2021). These studies have provided valuable insights into the behavior and distribution patterns of radionuclides in different aquatic environments (El-Reef et al., 2010; Sirin et al., 2019). However, there remains a significant knowledge gap regarding the natural distribution and activity ratios of radioactive materials in wetland environments, particularly those near nuclear power plants. The Longluan Wetland (LLW), situated within Kenting

National Park (KNP) in Taiwan and less than one kilometer from the Maanshan Nuclear Power Plant (NPP), provides an ideal location to address this research gap. Previous studies in Taiwan have predominantly focused on soil radioactivity (Chen et al., 2024; Huang et al., 2022, 2025; Tsai et al., 2008, 2011; Weng, 1996), with limited attention to wetland and lake sediments.

It is important to highlight that the Maanshan NPP has been operational since 1984. As the plant is set to begin decommissioning in 2025, gaining a thorough understanding of the current radiological conditions and the environmental factors affecting the surrounding ecosystem is both timely and essential. Therefore, this research is framed as a post-operational scientific assessment aimed at establishing an important radiological baseline before decommissioning activities start. The study goes beyond simple monitoring; it also explores the fundamental geochemical and physical processes that influence the distribution of radionuclides in this unique tropical wetland.

This study aims to (1) investigate the spatial distribution patterns of artificial and natural radionuclides (^{137}Cs , ^{40}K , ^{226}Ra , and ^{232}Th) in the LLW sediments (Tsabaris et al., 2007; Ugbede et al., 2020), (2) examine relationships between sediment properties and radionuclide activities (Lu et al., 2008; Suresh et al., 2012), (3) evaluate activity ratios ($^{40}\text{K}/^{226}\text{Ra}$, $^{40}\text{K}/^{232}\text{Th}$, and $^{232}\text{Th}/^{226}\text{Ra}$) to assess potential geochemical processes, (4) assess potential radiological risks (Ogundele et al., 2018), and (5) establish baseline data for future environmental monitoring programs. The findings will provide valuable insights into radionuclide behavior in wetland ecosystems and contribute to radiation protection strategies (Qureshi et al., 2014; Harikrishnan et al., 2018; Sirin, 2019).

Methods and materials

Study area

The Lunglun wetland (LLW) is located in Kenting National Park (21°57'N, 120°49'E), southern Taiwan, and covering approximately 1.75 km² with water depths of 2–3 m. The site experiences a tropical monsoon climate (Köppen climate classification: Am), with an annual mean temperature of 25.2 °C and precipitation of 2,200 mm, characterized by distinct

wet (May–October) and dry (November–April) seasons. The wetland lies less than one kilometer from the Maanshan NPP, which has been operational since 1984. The Maanshan NPP consists of two pressurized water reactors (PWRs), each with a generation capacity of approximately 951 MW. In normal, controlled operation, PWRs may release low levels of monitored liquid effluents containing fission and activation products, such as Cesium-137 (^{137}Cs) and Cobalt-60 (^{60}Co). Therefore, the presence of artificial radionuclides like ^{137}Cs is a key indicator of potential plant-related contamination in the wetland sediments.

The wetland's hydrology is maintained by monsoon rainfall and treated domestic wastewater, with occasional typhoon events contributing significant precipitation during summer. The morphology creates a distinctive water circulation pattern flowing from northeast/southeast inlets toward the northwest outlet (Fig. 1). This flow pattern, combined with shallow depth, promotes active sediment–water interactions that influence radionuclide distribution and biogeochemical processes.

The absence of other industrial activities in the vicinity makes LLW particularly suitable for investigating potential impacts from the NPP operation. Previous studies have established baseline data on water quality parameters and environmental chemistry characteristics (Chuang et al., 2021; KNP, 2025). The site's proximity to Maanshan NPP, well-documented environmental parameters, and relatively stable ecosystem make it an ideal location for studying both natural and anthropogenic radioactivity in a tropical wetland environment.

Sample collection and treatment

Surface sediment samples (0–20 cm) were collected from fifty locations across LLW on July 11, 2022, following three consecutive days of clear weather to minimize precipitation-induced variations. Sampling points were distributed in a systematic grid pattern with 100–250-m intervals, adjusted according to site accessibility (Fig. 1). All sampling locations were recorded using a differential GPS system (GARMIN GPSMAP 67, Taipei, Taiwan). Samples were collected using a long-handled stainless steel sampler and immediately sealed in clean polyethylene bags, then transported to the laboratory in ice-cooled containers to maintain sample integrity.

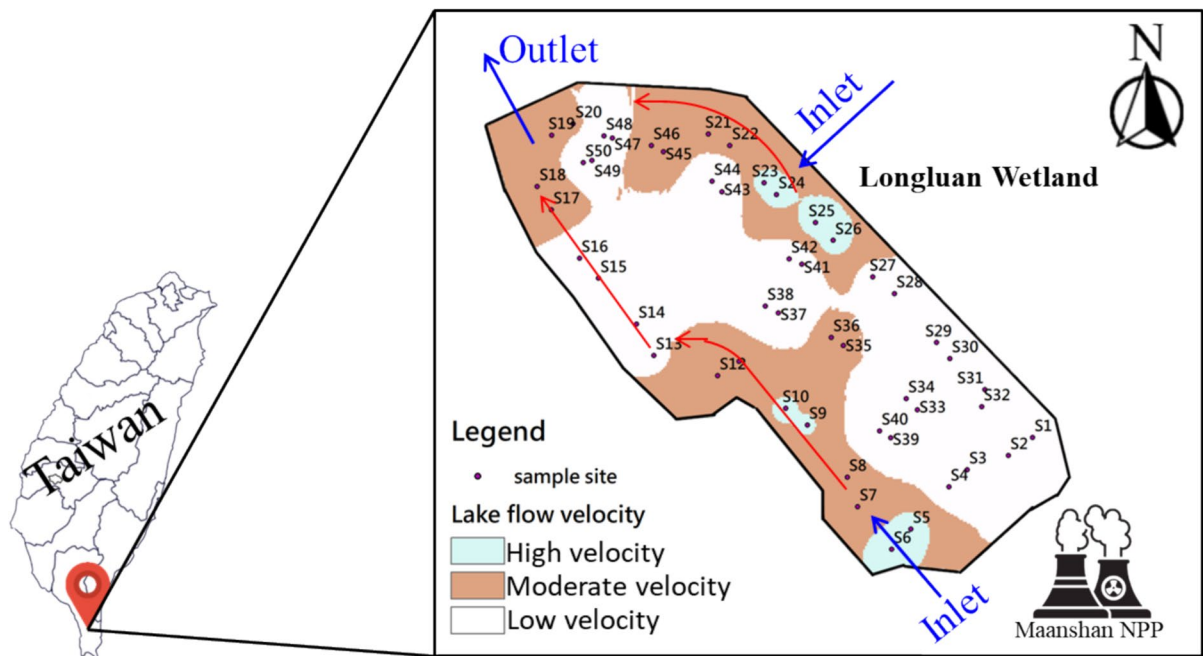


Fig. 1 Schematic diagram showing sampling locations and their corresponding site codes. Arrows indicate the flow direction, and the sites are color coded based on the level of radionuclide activity

In the laboratory, samples were spread on plastic trays and air-dried at room temperature (25 ± 2 °C) for 14 days until constant mass was achieved. After drying, visible organic debris and stone fragments were manually removed, and samples were homogenized using a ceramic mortar and pestle. For radioactivity analysis, approximately 150 g of each homogenized sample was passed through a 2-mm sieve and transferred to cylindrical containers (6.2 cm diameter $\times$ 4.5 cm height). The containers were sealed airtight and stored for 28 days before measurement to ensure secular equilibrium between ^{226}Ra , ^{232}Th , and their respective decay products (Ogundele et al., 2018).

Sediment properties analyses

Sediment physicochemical properties were analyzed following standard procedures. Sediment pH was measured using a calibrated pH meter (Thermo Scientific Orion Star A211) in a 1:2.5 sediment-to-deionized water suspension (w/v) after 30-min equilibration. Electrical conductivity (EC) was measured

using a conductivity meter (Thermo Scientific Orion 3-Star) in a 1:5 sediment-to-water extract (w/v).

Organic matter (OM) content was determined by the loss-on-ignition method, where samples were heated at 550 °C for 4 h. For particle size analysis, samples underwent a two-step pretreatment: (1) organic matter removal using 30% H_2O_2 and (2) carbonate removal using 1 M sodium acetate buffer (pH 5.0). The pretreated samples were then dispersed with sodium hexametaphosphate and analyzed using the combined sieve-pipette method following Gee and Bauder (1986).

Measurements of activity of radionuclides

Gamma spectrometric analysis was performed using a high-purity germanium (HPGe) detector (ORTEC, GEM40P4-79-SMP) with 40% relative efficiency and energy resolution of 1.85 keV FWHM at 1332.5 keV (^{60}Co). The detector was housed in a 10-cm-thick lead castle lined with copper to minimize background radiation. Energy calibration was conducted using a certified mixed radionuclide source containing ^{109}Cd , ^{57}Co , ^{203}Hg , ^{51}Cr , ^{113}Sn , ^{85}Sr , ^{137}Cs , ^{60}Co , and ^{88}Y ,

while efficiency calibration employed NIST-traceable reference materials with similar geometry and density to the samples, covering energies from 88 to 2000 keV. Self-absorption corrections were applied following Aközcan (2018), using sample density measurements and experimental transmission factors.

Activity concentrations were determined using the following gamma-ray photopeaks: ^{40}K (1460.8 keV), ^{137}Cs (661.66 keV), and ^{232}Th (583.0 keV via ^{208}Tl). The activity of ^{226}Ra was determined from the weighted average of its daughter ^{214}Bi photopeaks (609.3, 1120.3, and 1764.5 keV), as these provided a more distinct signal with less spectral interference than the ^{214}Pb photopeaks in our samples. Each sample was measured for 30,000 s, with background spectra collected weekly under identical measurement conditions. Counting uncertainties were calculated considering peak area statistics, calibration uncertainties, and sample preparation factors, all reported at the 1 σ confidence level.

The minimum detectable activities (MDAs) were calculated using Currie's formula at the 95% confidence level, yielding values of ^{40}K (16.3 ± 1.8 Bq/kg), ^{232}Th (3.1 ± 0.5 Bq/kg), ^{226}Ra (2.2 ± 0.3 Bq/kg), and ^{137}Cs (1.1 ± 0.2 Bq/kg).

Quality assurance and quality control (QA/QC)

The laboratory implemented comprehensive quality control procedures, including daily system performance checks of the HPGe detector and its lead shield assembly to ensure measurement integrity. Quality control protocols comprised weekly verification of detector performance using standard radiation

sources, specifically monitoring the 661.6 keV peak efficiency of ^{137}Cs and the energy calibration stability through ^{60}Co 1332.5 keV peak position and FWHM measurements. System stability was further validated through routine analysis of blank samples and control standards on a weekly basis. The laboratory's analytical competence has been continuously verified through successful participation in IAEA proficiency testing programs from 2017 to 2023.

Radiological hazard assessment

Radiological hazard indices were calculated to evaluate potential radiation exposure risks from sediment samples. The radium equivalent activity (Ra_{eq}), which provides a single index for gamma radiation hazards, was calculated using Eq. (1) (Ogundele et al., 2018):

$$Ra_{eq} \left(\frac{\text{Bq}}{\text{kg}} \right) = A_{Ra} + 1.43A_{Th} + 0.077A_k \quad (1)$$

The external hazard index (H_{ex}), which should be less than unity for safe use, was determined using Eq. (2) (Harikrishnan et al., 2018):

$$H_{ex} = \frac{A_{Ra}}{370} + \frac{A_{Th}}{259} + \frac{A_k}{4810} \quad (2)$$

The external absorbed dose rate in air (DR_{ex}) at 1 m above the ground surface and the annual effective dose equivalent ($AEDE_{ex}$) were calculated using Eqs. (3) and (4), respectively (Gaafar et al., 2022):

$$DR_{ex} \left(\frac{\text{nGy}}{\text{h}} \right) = 0.462A_{Ra} + 0.604A_{Th} + 0.0417A_k \quad (3)$$

$$AEDE_{ex} \left(\frac{\mu\text{Sv}}{\text{y}} \right) = DR_{ex} \left(\frac{\text{nGy}}{\text{h}} \right) \times 8760 \left(\frac{\text{h}}{\text{y}} \right) \times 0.2 \times 0.7 \left(\frac{\text{Sv}}{\text{Gy}} \right) \times 10^{-3} \quad (4)$$

where A_{Ra} , A_{Th} , and A_k represent the activities (Bq/kg) of ^{226}Ra , ^{232}Th , and ^{40}K , respectively. 8760 represents annual hours, 0.2 is the outdoor occupancy factor, 0.7 Sv/Gy is the conversion coefficient from absorbed dose in air to effective dose in humans, and 10^{-3} converts nGy to μGy .

Statistical analysis

Statistical analyses were conducted using S Plus (V6.1, Insightful, USA) and Microsoft Excel software. The Kolmogorov–Smirnov test was applied to assess data normality at a significance level of 0.05

($\alpha=0.05$). Descriptive statistics were computed for all measured parameters in both high and low-activity groups. Pearson correlation analysis was performed to evaluate the relationships between radionuclide activities and sediment properties across all groups (overall, high-, and low-activity groups). Differences among radionuclides were examined using one-way analysis of variance (ANOVA). Spatial distribution of activities was interpolated using the inverse distance weighted (IDW) method, and the spatial distribution maps were generated using ArcGIS Pro (version 10.4, ESRI Inc., USA).

Results and discussion

Radionuclide activities and distribution characteristics

In total, 50 sediment samples were collected from LLW and were analyzed for gamma-emitting radionuclides ^{137}Cs , ^{40}K , ^{226}Ra , ^{228}Ra , and ^{232}Th . The activity of ^{137}Cs was below the minimum detectable activity (MDA) in all sediment samples. As ^{137}Cs is a key indicator for both global fallout from historical nuclear testing and potential fission product releases from nuclear power plants, its absence strongly suggests that the wetland has not been significantly

impacted by radiological contamination from these major historical events or the operational activities of the adjacent Maanshan NPP. In contrast, the natural radionuclides ^{40}K , ^{226}Ra , and ^{232}Th were detected in all sediment samples. Table S1 lists the measured activities with uncertainties at one-standard deviation and GPS coordinates.

The average activity ratio of ^{232}Th to ^{228}Ra was 0.98 ± 0.10 with a significant positive correlation ($r=0.97$, $p<0.001$), suggesting secular equilibrium of thorium series in the sediments (Khan et al., 2023). Since ^{228}Ra is a progeny of thorium series, ^{232}Th activity concentrations were representative of thorium series activity (Khan et al., 2021).

The ^{40}K , ^{226}Ra , and ^{232}Th activities showed heterogeneous spatial distributions in the wetland sediments (Fig. 2a–c). The higher activities were found in the center and southeastern areas, while lower activities were observed along the wetland edges from the inlet to the outlet areas. To investigate potential mechanisms responsible for this spatial variation, samples were categorized into high- and low-activity regions using the mean ^{40}K concentration (400.7 Bq/kg) as baseline, which approximates the worldwide median soil concentration of 400 Bq/kg (UNSCEAR, 2000). This categorization resulted in 28 samples from high-activity areas and 22 from low-activity areas.

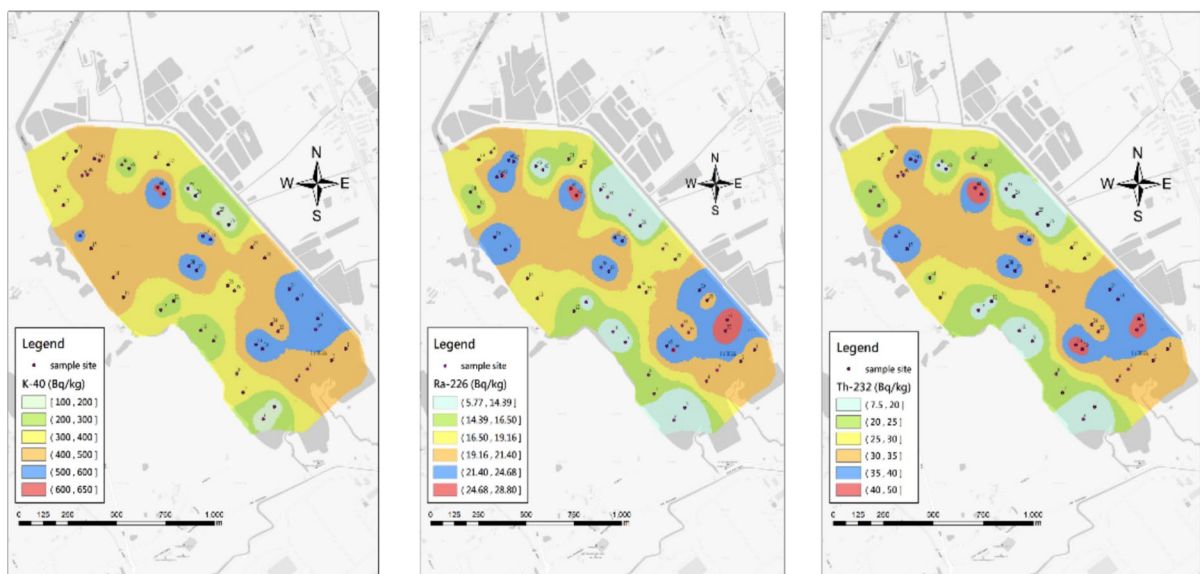


Fig. 2 a–c The spatial distribution maps of the studied nuclide in LLW sediments; **a** ^{40}K , **b** ^{226}Ra , and **c** ^{232}Th

Table 1 Statistical summary of specific activities (Bq/kg) of ^{40}K , ^{232}Th , and ^{226}Ra in sediments: analysis of total dataset and classification by activity levels

Parameters	^{40}K			^{232}Th			^{226}Ra		
	Total	High	Low	Total	High	Low	Total	High	Low
Min ^a	118.0	413.1	118.0	7.5	24.2	7.5	5.8	17.3	5.8
Max ^b	624.7	624.7	390.5	58.3	58.3	31.0	28.8	28.8	19.1
CV, % ^c	35.2	11.1	34.1	39.2	18.6	36.8	30.8	12.2	30.7
Kurtosis	− 0.80	− 0.25	− 1.27	− 0.46	2.26	− 0.76	− 0.42	− 0.17	− 0.83
Skewness	− 0.49	0.45	− 0.22	− 0.02	0.76	0.19	− 0.52	0.26	− 0.39
<i>p</i> value [*]	0.35	0.84	0.88	0.81	0.84	0.88	0.72	0.98	0.73
Number	50	28	22	50	28	22	50	28	22

^aMinimum; ^bmaximum;

^ccoefficient of variation;

^{*}Kolmogorov–Smirnov test

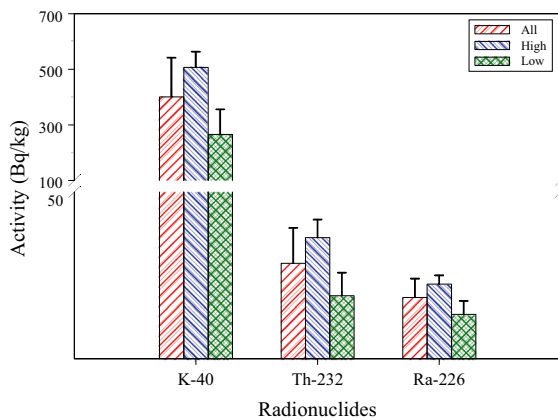


Fig. 3 Grouped bar chart comparing the mean activities of ^{40}K , ^{226}Ra , and ^{232}Th . Bars represent the mean activity for the entire dataset (all), the low-activity subgroup (low), and the high-activity subgroup (high). Subgroups were categorized based on the mean activity of ^{40}K (400.7 Bq/kg). Error bars indicate the standard deviation (SD)

The spatial distribution patterns of radionuclides in wetland sediments are closely related to sediment particle size distribution and organic matter content (Li et al., 2024; Ren et al., 2024). The transport and deposition of sediments in wetland systems can significantly influence the redistribution of naturally occurring radionuclides (Khurram et al., 2023).

Descriptive statistics for the radionuclide activities are summarized in Table 1. The moderate coefficient of variation (CV) values for ^{40}K , ^{226}Ra , and ^{232}Th confirm the notable degree of spatial variability. Despite this, the data's normality (Kolmogorov–Smirnov test, $p > 0.05$), along with skewness and kurtosis values, suggest a common and relatively uniform geological source. To further investigate this spatial variability, samples were categorized into low- and high-activity subgroups. As illustrated in the

Table 2 Comparison of radionuclide activities (Bq/kg) in LLW sediments with regional soils and rocks

Source/material	^{40}K	^{226}Ra	^{232}Th	References
LLW sediment	400.7	18.4	29.1	This study
Local soil	344.4	18.6	26.5	Chen et al., 2024
Shale	813.0	32.0	51.0	Weng, 1996
Sandstone	539.0	19.0	50.0	Weng, 1996
Limestone	80.0	17.0	5.1	Weng, 1996

Note: ^{226}Ra activity is used as a proxy for ^{238}U , assuming secular equilibrium

grouped bar chart in Fig. 3, a clear and significant difference emerges between these subgroups. The mean activities in the high-activity zones are approximately 1.7 to 2.0 times greater than those in the low-activity zones. This distinct separation strongly indicates that while the radionuclide source is geologically consistent, their final distribution is spatially modulated by localized physicochemical factors, supporting our hypothesis that depositional environments rich in fine sediment and organic matter act as preferential sinks.

The surface sediments comprise soil particles and particulate organic matter from the wetland surroundings, transported by runoff from wetland banks and inlet flows. The distribution of natural radionuclides in sediments is primarily influenced by local geological and geographical conditions (Otansev, 2012; Aközcan, 2018). The LLW region is situated within the Maanshan Formation of the Hengchun Peninsula, which represents the southern part of the Taiwan accretionary wedge (Huang et al., 2001). The Maanshan Formation, deposited during the Late Miocene to Early Pleistocene, consists predominantly of deep-marine turbidite sequences characterized by alternating sandstone and mudstone layers (Garzanti et al., 2023). These sedimentary sequences were formed

through the complex tectonic processes associated with the oblique arc-continent collision between the Eurasian plate and the Philippine Sea plate (Huang et al., 2018; Zhang et al., 2023).

The local geology primarily governs the distribution of natural radionuclides in the wetland. As presented in Table 2, the radionuclide activities in LLW sediments closely mirror those found in nearby soils (Chen et al., 2024), exhibiting an identical activity trend of $^{40}\text{K} > ^{232}\text{Th} > ^{226}\text{Ra}$. Furthermore, this pattern, particularly the higher activity of ^{232}Th relative to ^{226}Ra , aligns with the geochemical signature of regional sandstone and shale (Weng, 1996). This strong correlation indicates that the LLW sediments are predominantly derived from the weathering and erosion of local soils and the underlying Maanshan Formation, thus confirming the geological origin of their radionuclide content.

As shown in Table 3, the radionuclide activities in LLW sediments are modest on a global scale. They are notably lower than levels reported for geologically distinct regions, such as the freshwater lakes in Pakistan (Afzal et al., 2022; Khan et al., 2023). However, they are comparable to findings from other wetland systems in Italy and Iran. This comparison suggests that the local Maanshan Formation is not a significant source of primordial radionuclide enrichment. This finding is crucial, as it establishes a non-elevated regional baseline and confirms the absence of significant natural radioactive accumulation in the study area.

Correlation of radioactivity and sediment properties

Linear regression analysis of radioactivity relationships between $^{232}\text{Th}/^{226}\text{Ra}$, $^{226}\text{Ra}/^{40}\text{K}$, and $^{232}\text{Th}/^{40}\text{K}$

showed significant linearity ($r=0.95\text{--}0.97$, $p<0.001$) for all three pairs of radionuclides (Figs. 4a–c). Both high and low radioactivity samples exhibited significant positive correlations ($r=0.67\text{--}0.89$ and $r=0.95\text{--}0.96$ respectively, $p<0.001$), suggesting common geological sources and similar environmental behavior patterns (Khan et al., 2023; Krmar et al., 2009).

Despite the relatively small wetland area (1.75 km²), individual radionuclide activities varied by five- to eight-fold (Table 1), and their spatial distribution showed distinct patterns related to the wetland's flow dynamics. To better analyze these trends, the sampling sites were grouped into three distinct zones based on primary hydro-sedimentary characteristics (Fig. 1): area B, the eastern inflow zone directly influenced by the main water inlet and characterized by higher water velocity; area C, the central depositional basin with low water velocity that facilitates the accumulation of fine-grained sediments; and area A, the shoreline transitional zone with intermediate hydro-dynamic conditions.

This grouping reveals a clear pattern: radioactivity levels are lowest in the high-velocity inflow zone and highest in the low-velocity depositional basin. For example, samples S23–S26 from the inflow zone (area B) showed low ^{40}K activities of 128–179 Bq/kg, whereas samples S37–S40 from the central depositional basin (area C) exhibited the highest activities, ranging from 554 to 604 Bq/kg. Similar spatial trends were observed for ^{226}Ra and ^{232}Th (Fig. 2b and c).

To investigate the underlying factors for this variation, organic matter content was analyzed concurrently. Furthermore, 12 representative sediment

Table 3 Specific activities (Bq/kg) of radionuclides in sediments from global freshwater basins and wetland systems

Location/country	^{40}K	^{226}Ra	^{232}Th	References
LLW, Taiwan	400.7	18.4	29.1	Present study
Namal Lake, Pakistan	512.4	35.2	45.8	Afzal et al., 2022
Calabria wetlands, Italy	446.0	24.0	37.4	Caridi et al., 2021
Van Lake Basin, Turkey	478.5	31.2	42.4	Zorer et al., 2019
Anzali wetland, Iran	385.4	23.4	28.1	Zare et al., 2016
Chashma Lake, Pakistan	552.3	38.5	48.2	Khan et al., 2023
Borcka Dam lake, Turkey	396.0	12.2	14.1	Sirin, 2019
Karacaoren II dam lake, Turkey	812.0	79.6	72.4	Apaydin et al., 2019
Eko-Ende Dam, Nigeria	1356.0	55.0	48.2	Ogundele et al., 2018
Burullus Lake, Egypt	312.0	14.3	20.2	El-Reefy et al., 2010
Wei River, China	833.0	21.8	33.1	Lu et al., 2008

Fig. 4 **a–c** Linear regression relationships between the activities of radionuclides: ^{232}Th vs. ^{226}Ra **a**, ^{226}Ra vs. ^{40}K **b**, and ^{232}Th vs. ^{40}K **c**

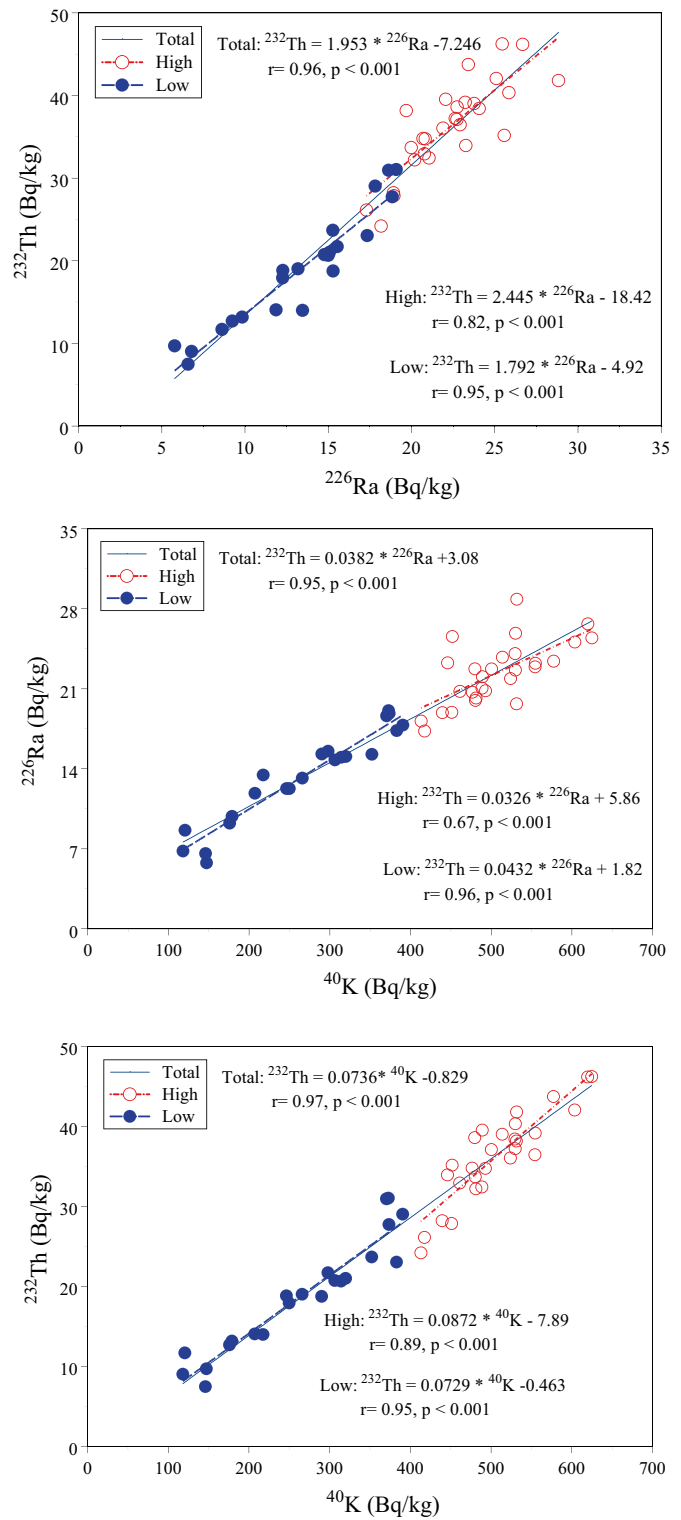


Table 4 Mean $\pm$ SD specific activities (Bq/kg) and grain size fractions [sand (0.05–2 mm), silt (0.002–0.05 mm), clay (<0.002 mm)] in sediments from three selected areas ($n=4$)

Location	^{40}K , Bq/kg	^{226}Ra , Bq/kg	^{232}Th , Bq/kg	Sand, %	Silt, %	Clay, %
A area	456 $\pm$ 49	20.5 $\pm$ 3.2	32.0 $\pm$ 7.9	27.8 $\pm$ 3.6	35.2 $\pm$ 4.1	35.2 $\pm$ 7.6
A area	413–513	17.3–23.8	24.2–39.0	22.8–31.3	31.3–39.6	28.3–45.9
B area	148 $\pm$ 34	8.6 $\pm$ 1.3	11.7 $\pm$ 1.9	46.1 $\pm$ 3.0	31.8 $\pm$ 3.3	26.4 $\pm$ 7.4
B area	118–179	6.8–9.8	9.0–13.2	42.0–49.0	28.7–35.1	20.6–35.9
C area	573 $\pm$ 23	23.7 $\pm$ 1.0	45.8 $\pm$ 8.5	31.8 $\pm$ 10.4	29.2 $\pm$ 8.9	39.0 $\pm$ 2.9
C area	554–604	22.9–25.1	39.2–58.3	21.3–42.8	21.5–37.3	35.6–42.3
p value*	<0.001	<0.001	<0.001	0.009	0.41	0.05

* p value was conducted by ANOVA analysis to compare the difference of three areas

samples were selected from these three distinct zones—areas A, B, and C (corresponding to samples S13–S16, S23–S26, and S37–S40, respectively)—for detailed particle size analysis.

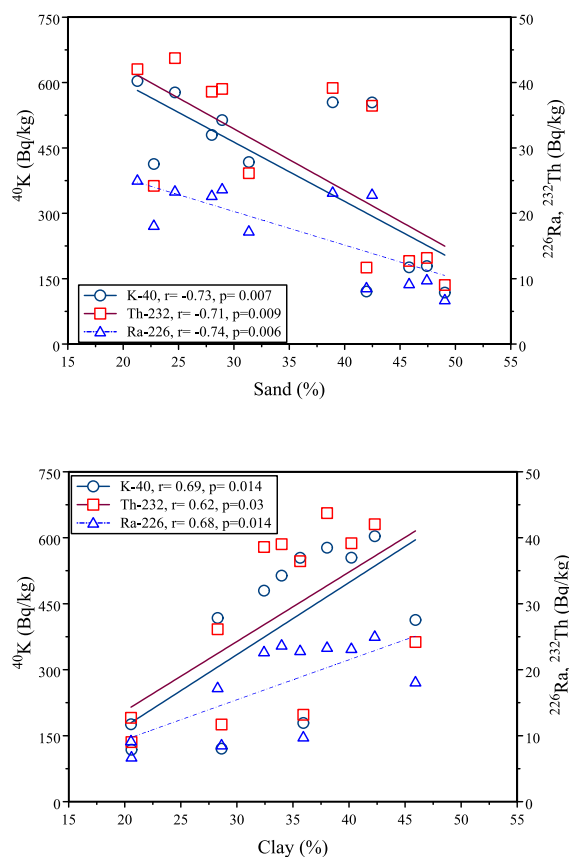
**Fig. 5** a and b Linear regression relationships between radionuclide activities (^{40}K , ^{226}Ra , and ^{232}Th) and sediment grain size fractions: sand a and clay b

Table 4 presents activities and sediment composition data across the three areas. Radioactivity followed the order $C > A > B$, with area C showing significantly higher levels than area B. Area B had significantly higher sand percentage than areas C and A ($p=0.01$), while its clay percentage was lower than area C ($p=0.05$).

Linear regression analysis revealed that radionuclide activities have a significant positive correlation with clay percentage ($r=0.62$ – 0.69 , $p<0.05$) and a negative correlation with sand percentage (Fig. 5a and b). This confirms that clay content is a key factor influencing radionuclide distribution. In comparison, organic matter (OM) content demonstrated a stronger and more dominant positive correlation with all three radionuclides ($r>0.85$, $p<0.001$; Figs. 6a–c). This suggests that while both fine-grained texture and OM are critical, the high affinity of OM for radionuclide complexation may serve as the primary controlling mechanism for their accumulation in these sediments, a finding consistent with recent studies (Darwish et al., 2013; Khan et al., 2021).

Areas with reduced flow velocity tend to accumulate more fine-grained sediments and organic matter, resulting in higher radioactivity levels (Duong et al., 2023; Navas et al., 2011). The primary mechanism governing this is the transport and deposition of radionuclide-associated particulate matter. In high-energy environments, fine particles with adsorbed radionuclides are kept in suspension and transported with the flow. As water moves into lower-energy zones, the reduced hydrodynamic force allows these particles to settle via gravity. In river systems, this deposition typically occurs on floodplains, in wider basins, or on the inner bends of meanders, while in a semi-enclosed

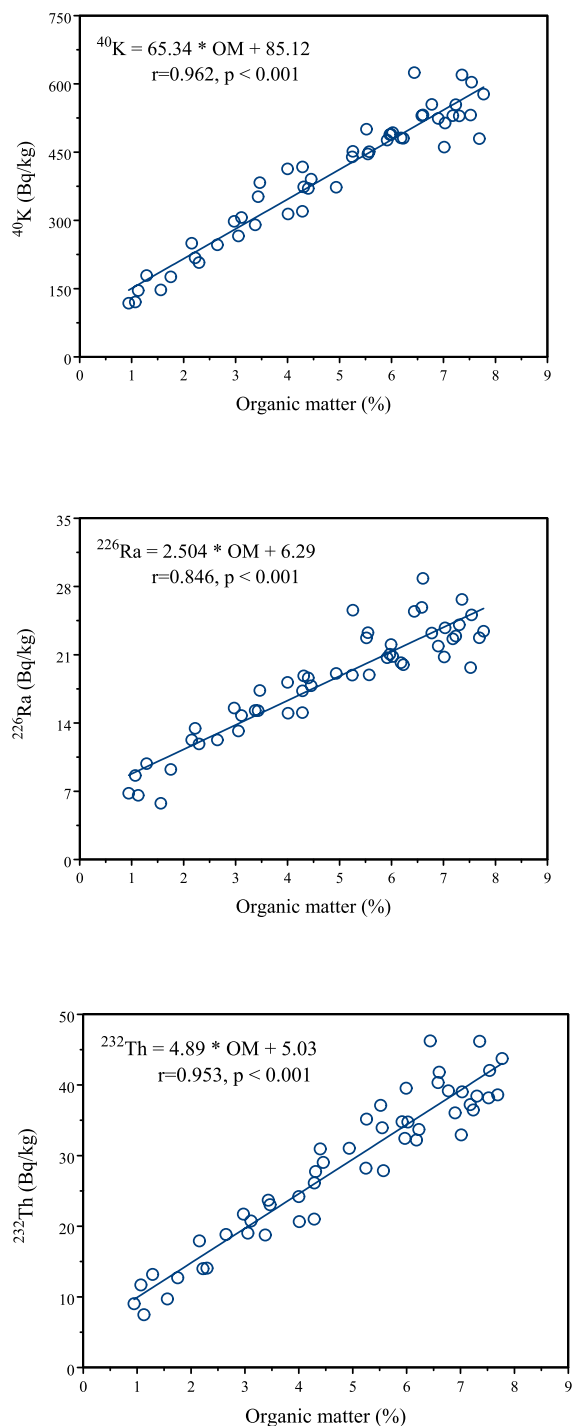


Fig. 6 a–c Linear regression relationships between organic matter content in sediments and the specific activities of ^{40}K a, ^{226}Ra b, and ^{232}Th c

system like the Lungluan Wetland, it happens in areas away from the direct flow path (El-Reefy et al., 2010; Kang et al., 2024).

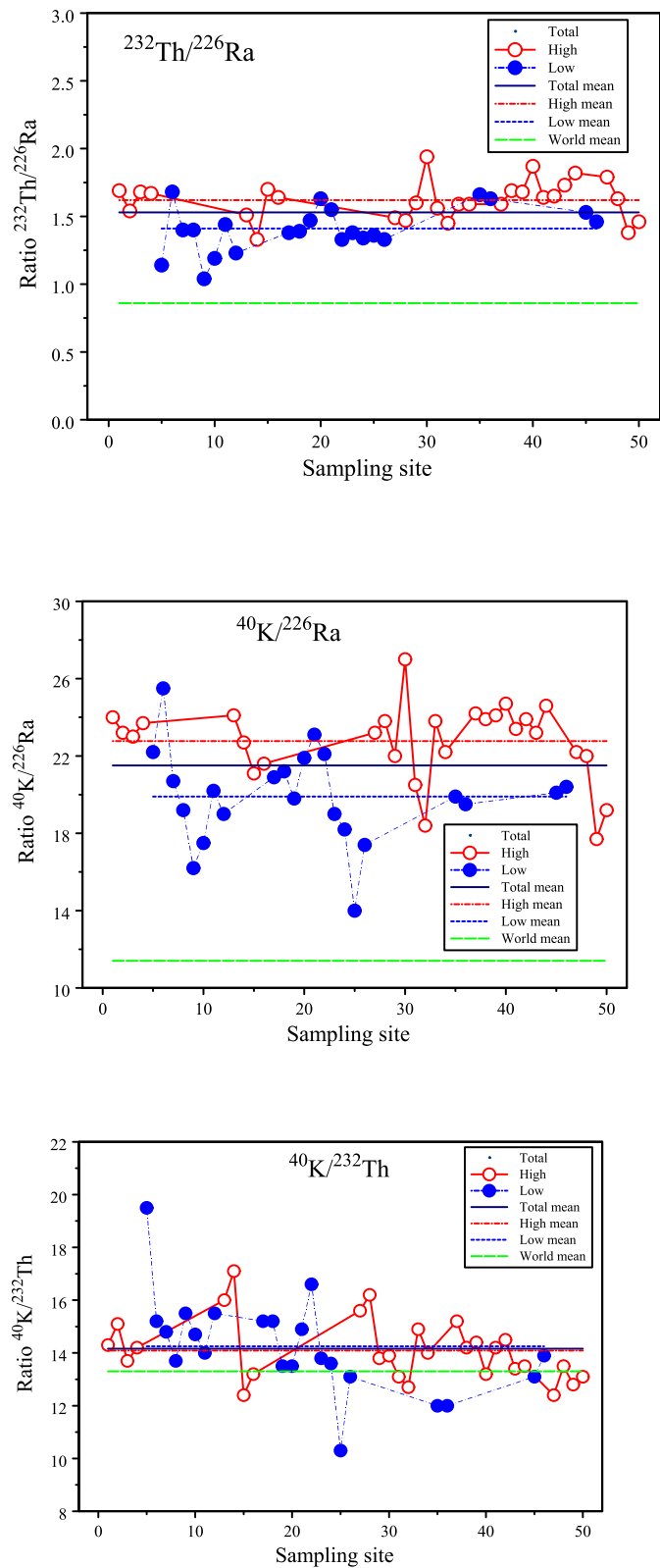
The reason these fine-grained sediments are so effective at concentrating radionuclides lies in their microscopic properties. These particles ($< 63 \mu\text{m}$), such as clay and silt, possess a large specific surface area and a net negative surface charge, which enhances their capacity to adsorb and bind positively charged radionuclide ions. Concurrently, organic matter, which often coats these fine particles or exists as discrete aggregates, contains abundant functional groups (e.g., carboxyl, hydroxyl) that actively chelate and complex radionuclides. Therefore, the formation of radionuclide “hotspots” is dictated by the interplay between the system’s hydrodynamics, which determine the precise locations of these depositional zones, and the physicochemical properties of the settling particles, which ensure the efficient retention of radionuclides.

Activity ratios

Activity ratios between different radionuclides provide valuable insights into geochemical processes and environmental conditions in sedimentary environments (Navas et al., 2002; Tsabaris et al., 2007). These ratios can reflect both the equilibrium state of radionuclides and the influence of environmental factors, particularly in wetland systems where unique hydrological and geochemical conditions prevail. Studies of international wetlands have shown that the activity ratios in wetland sediments often differ from those in surrounding terrestrial soils, reflecting the unique depositional and biogeochemical processes in these environments (Zare et al., 2016).

The radioactivity ratios for overall, high-activity, and low-activity samples are shown in Figs. 7a–c. The $^{232}\text{Th}/^{226}\text{Ra}$ ratios ranged from 1.04 to 1.94 (mean: 1.53 ± 0.19), while $^{40}\text{K}/^{226}\text{Ra}$ ratios varied between 14.0 and 27.0 (mean: 21.5 ± 2.6), and $^{40}\text{K}/^{232}\text{Th}$ ratios spanned 10.3 to 19.5 (mean: 14.2 ± 1.5). These ratios showed relatively low variation, with CV values of 8.2–12.9% for both high and low radionuclide samples, indicating better consistency compared to previous studies that reported moderate variations of 15–35% in various aquatic environments (Hari Krishnan et al., 2018; Ugbede et al., 2020). Similar low variability patterns have been observed

Fig. 7 a–c Distribution of radionuclide activity ratios in sediments showing $^{232}\text{Th}/^{226}\text{Ra}$ **a**, $^{40}\text{K}/^{226}\text{Ra}$ **b**, and $^{40}\text{K}/^{232}\text{Th}$ **c**



in other wetland and lake systems, with CV values typically ranging from 10 to 20% (Sirin et al., 2019; Caridi et al., 2021), suggesting that controlled hydrological conditions in enclosed water bodies may contribute to more stable radionuclide ratio distributions.

The mean $^{232}\text{Th}/^{226}\text{Ra}$ activity ratio in our samples was 1.53, which is notably higher than the global soil median of approximately 0.86. This elevated ratio can be attributed to two main factors. Firstly, it likely reflects the natural geological signature of the watershed's source rocks, which may be inherently enriched in thorium compared to uranium. Secondly, and perhaps more significantly, it is a consequence of the distinct geochemical behaviors of thorium and radium during transport and deposition. ^{232}Th is known to be highly insoluble and particle-reactive, strongly adsorbing to fine-grained sediments and organic matter. In contrast, ^{226}Ra is relatively more soluble and mobile, particularly under certain environmental conditions, allowing it to be partially leached from sediments and transported in dissolved form. Therefore, the combination of a potentially Th-rich source and the preferential retention of Th over the more mobile Ra within the sediments leads to the observed elevated $^{232}\text{Th}/^{226}\text{Ra}$ ratio. This is further supported by the even higher ratio (1.62) found in the high-activity depositional zones, where conditions for Th adsorption are optimal.

Compared to updated global soil median ratios ($^{232}\text{Th}/^{226}\text{Ra}$: 0.86, $^{40}\text{K}/^{232}\text{Th}$: 13.3, $^{40}\text{K}/^{226}\text{Ra}$: 11.4) reported by Khan et al. (2023), our study showed notably higher average ratios for $^{232}\text{Th}/^{226}\text{Ra}$ and $^{40}\text{K}/^{226}\text{Ra}$, while the $^{40}\text{K}/^{232}\text{Th}$ ratio remained comparable. Similar elevated ratios have been observed in other wetland systems, attributed to the selective enrichment of specific radionuclides under wetland conditions (Darwish et al., 2013; El-Reefy et al., 2010). This pattern of elevated ratios in wetland environments has been linked to the unique physicochemical conditions that influence radionuclide mobility and retention. Specifically, factors such as lower pH and anoxic conditions, often found in organic-rich sediment layers, can increase the solubility and mobility of radium (Ra) relative to thorium (Th), which tends to be more strongly adsorbed to particulate matter. Furthermore, the high cation exchange capacity of clay minerals and organic matter preferentially retains certain ions, leading to the differential

enrichment observed in the activity ratios (Zorer et al., 2019).

High-activity samples exhibited significantly higher ratios for $^{232}\text{Th}/^{226}\text{Ra}$ (1.62 ± 0.14 vs 1.41 ± 0.17) and $^{40}\text{K}/^{226}\text{Ra}$ (22.8 ± 2.0 vs 19.9 ± 2.4) compared to low-activity samples ($p < 0.001$). However, $^{40}\text{K}/^{232}\text{Th}$ ratios showed no significant difference between high (14.1 ± 1.2) and low-activity samples (14.3 ± 1.8 , $p = 0.73$). This pattern suggests differential mobility and enrichment of radionuclides under wetland conditions, consistent with observations in other aquatic systems where hydrodynamic conditions influence radionuclide distributions (Caridi et al., 2021).

The distinct variations in ratios between high- and low-activity samples reflect differential enrichment patterns, with ^{40}K and ^{232}Th showing approximately 1.9-fold increases compared to a 1.68-fold increase for ^{226}Ra . This observation aligns with previous studies demonstrating the influence of environmental conditions on radionuclide mobility and distribution (Gaafar et al., 2022; Narayana & Rajashekara, 2010). Zorer et al. (2019) further demonstrated that variations in activity ratios can be attributed to differences in radionuclide transport mechanisms and their interactions with environmental matrices. For instance, ^{226}Ra , being more soluble, can be transported in dissolved form, while ^{40}K and ^{232}Th are predominantly associated with particulate matter.

In depositional zones, fine-grained sediments (the matrix) accumulate. Since these particles have a higher affinity for adsorbing Th and K, these zones become enriched in Th and K relative to Ra. The underlying chemical mechanism for this fractionation, particularly for thorium, is its strong tendency to form complexes with organic matter. Thorium (Th^{4+}) acts as a hard Lewis acid, forming strong covalent bonds with oxygen-containing functional groups (e.g., carboxyl and hydroxyl groups) that are abundant in humic substances. This complexation effectively immobilizes thorium within the organic-rich sediment matrix. This chemical mechanism is strongly supported by our data, specifically the very high correlation coefficient ($r > 0.85$) observed between ^{232}Th and organic matter content. In contrast, Radium (Ra^{2+}) is less prone to such strong complexation and remains more mobile in its ionic form, contributing to

the observed fractionation. This differential transport and deposition mechanism directly leads to the higher $^{232}\text{Th}/^{226}\text{Ra}$ and $^{40}\text{K}/^{226}\text{Ra}$ ratios observed in the high-activity, fine sediment areas of the wetland.

Under wetland conditions, particularly in areas with reduced flow and higher organic matter content, thorium tends to be less mobile than radium due to its lower solubility in low-oxygen environments (Khan et al., 2021). This behavior is reflected in the higher $^{232}\text{Th}/^{226}\text{Ra}$ ratios observed in high-activity samples, which typically correspond to areas with reduced flow velocity and higher organic matter content. Recent studies by Kang et al. (2024) have similarly demonstrated the significant influence of hydrodynamic conditions on ratio distributions in aquatic systems.

The spatial variations in activity ratios also correlate with sediment characteristics. Areas with higher clay content and organic matter typically show elevated $^{232}\text{Th}/^{226}\text{Ra}$ and $^{40}\text{K}/^{226}\text{Ra}$ ratios (El-Gamal et al., 2007; Madruga et al., 2014), consistent with our observations in the central wetland area. Recent studies in lake environments have shown that these correlations are particularly strong in depositional zones where fine sediments accumulate (Afzal et al., 2022), supporting our findings in the wetland system. These relationships suggest that particle size distribution and organic matter content play crucial roles in determining radionuclide ratios in wetland sediments, with implications for understanding radionuclide transport and fate in these environments.

Radiological hazard assessment and environmental implications

Several internationally recognized radiological indices were calculated to assess potential radiological hazards associated with the sediment samples (Afzal et al., 2022). These included radium equivalent activity (Ra_{eq}), external hazard index (H_{ex}), external absorbed dose rate in air (DR_{ex}), and external annual effective dose equivalents ($AEDE_{ex}$). These indices are particularly relevant for wetland environments where sediment–water interactions and biogeochemical processes can influence radionuclide mobility and potential exposure pathways (El-Reef et al., 2010; Zare et al., 2016). Figures 8a–d demonstrate the spatial variations of radiological hazard indices [Ra_{eq} (a), H_{ex} (b), DR_{ex} (c), and $AEDE_{ex}$ (d)] among the sampling sites.

The Ra_{eq} values ranged from 28.5 to 148.9 Bq/kg, with a mean of 90.8 ± 32.3 Bq/kg. High radioactivity samples showed higher values (114.4 ± 15.7 Bq/kg) compared to low radioactivity samples (60.8 ± 20.7 Bq/kg). These values are comparable to lake sediments in Turkey (113.2–224.7 Bq/kg; Aközcan et al., 2018) and river sediments (86.5–156.3 Bq/kg; Gaafar et al., 2022), while remaining well below the recommended limit of 370 Bq/kg (UNSCEAR, 2000). In wetland environments, Ra_{eq} values typically show spatial variations related to sediment composition and hydrological conditions, with higher values often associated with depositional zones where fine sediments accumulate (Zare et al., 2016).

The H_{ex} values ranged between 0.08 and 0.40, with means of 0.31 and 0.16 for high and low radioactivity samples respectively. These values align with global river sediments (0.23–0.48; Ogundele et al., 2018) and recent lake studies (0.18–0.45; Khan et al., 2023), remaining below the recommended limit of unity. Studies in wetland systems have shown that H_{ex} values can be influenced by seasonal variations in water levels and associated changes in sediment characteristics (Sirin et al., 2019). The spatial distribution of H_{ex} values often correlates with sediment grain size distribution, with higher values typically observed in areas dominated by fine-grained sediments (Caridi et al., 2021).

The DR_{ex} values ranged from 13.2 to 69.1 nGy/h with a mean of 42.3 ± 15.1 nGy/h, below the worldwide average of 59 nGy/h. The $AEDE_{ex}$ values varied from 0.016 to 0.085 mSv/y with a mean of 0.052 ± 0.019 mSv/y is well below the 1.0 mSv/y dose limit recommended by the International Commission on Radiological Protection (ICRP, 2007) for the general public. These values are consistent with those reported for other wetland environments (Zare et al., 2016), suggesting similar radiological exposure patterns in comparable ecosystems. Recent studies have demonstrated that both DR_{ex} and $AEDE_{ex}$ values in wetland sediments show strong correlations with organic matter content and clay fraction (Apaydin et al., 2019; Khan et al., 2023).

The comprehensive analysis of radionuclide activities and radiological hazard indices reveals several key environmental implications. The strong correlations between radionuclide activities and sediment characteristics (clay content: $r=0.62$ – 0.69 , $p<0.05$; organic matter: $r=0.85$ – 0.91 , $p<0.001$) demonstrate

that sediment properties can serve as preliminary indicators for potential radioactivity distributions. Fine particles and organic matter content are particularly useful as screening tools for identifying areas of potential radionuclide accumulation (Caridi et al., 2021; Khan et al., 2023).

The spatial patterns of radionuclide activities and hazard indices clearly demonstrate the influence of wetland hydrodynamics on radionuclide distribution. Areas with reduced flow velocity (central wetland) consistently showed higher activities (1.9-fold for ^{40}K and ^{232}Th , 1.68-fold for ^{226}Ra) compared to inlet/outlet regions, functioning as natural sinks for radioactive elements (El-Reef et al., 2010; Zare et al., 2016). The strong correlations between radionuclides ($r=0.95\text{--}0.97$, $p<0.001$) and their consistent activity

ratios ($\text{CV}=8.2\text{--}12.9\%$) suggest their potential use as natural tracers for sediment transport studies, assessment of erosion–deposition dynamics, and evaluation of wetland restoration projects (Afzal et al., 2022; Gaafar et al., 2022).

Fine-grained sediments typically show higher indices due to their enhanced radionuclide retention capacity (Aközcan et al., 2018), with strong positive correlations observed between clay content and radiological indices (Khan et al., 2023). The influence of organic matter content on radionuclide binding and retention has been well documented (Apaydin et al., 2019), while water level fluctuations and seasonal variations have been shown to affect radionuclide distribution patterns (Zorer et al., 2019). In depositional environments, distinct radiological signatures have

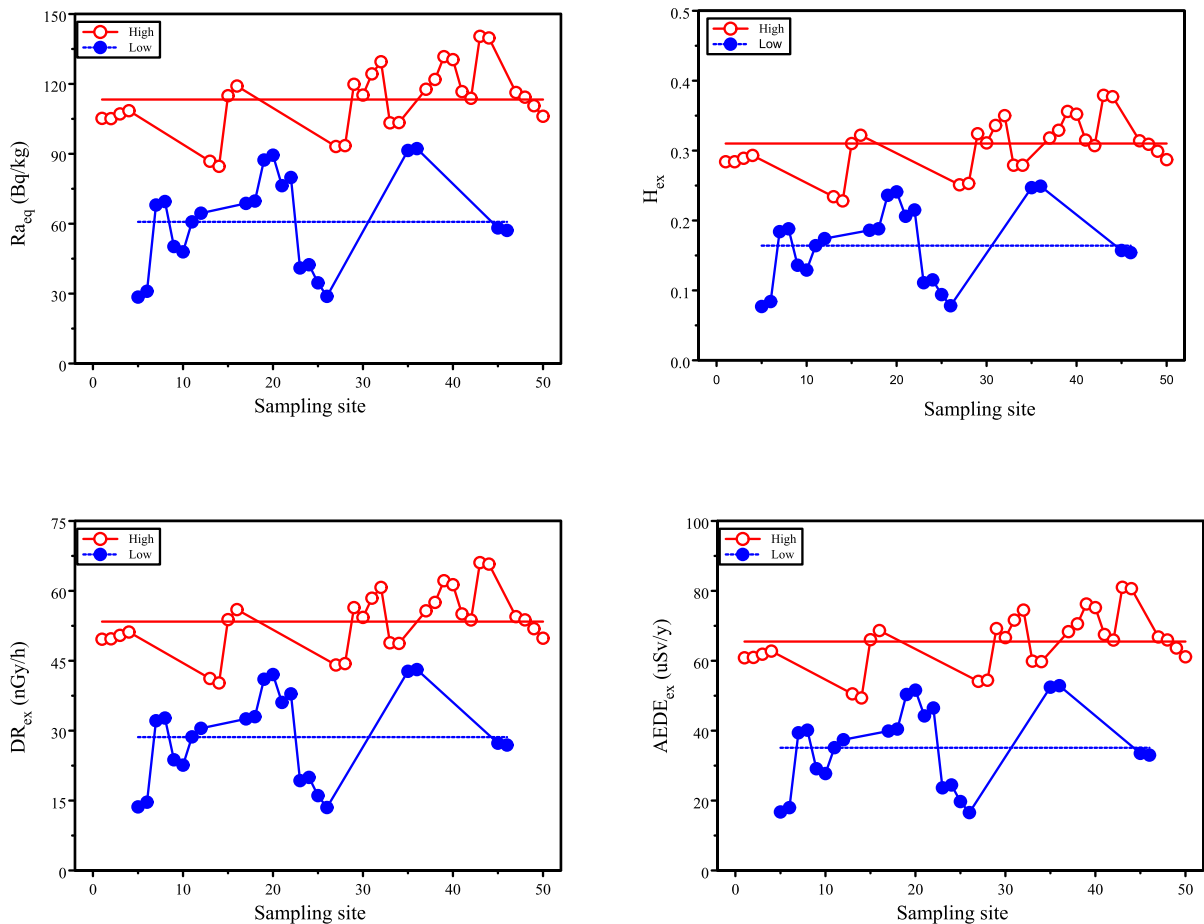


Fig. 8 a–d Spatial variation of radiological hazard indices in sediments: **a** radium equivalent activity (Ra_{eq} , Bq kg^{-1}), **b** external hazard index (H_{ex}), **c** external absorbed dose rate

(DR_{ex} , nGy h^{-1}), and **d** annual external effective dose equivalent (AEDE_{ex} , $\mu\text{Sv y}^{-1}$)

been observed, particularly in areas where fine sediments accumulate (El-Reef et al., 2010).

These findings suggest several key considerations for optimizing monitoring strategies, including focus on depositional zones with high fine particle content, regular monitoring of areas with elevated organic matter, and consideration of seasonal hydrodynamic variations (Sirin et al., 2019; Khan et al., 2023). The integration of sediment property analysis in radioactivity assessments has proven particularly effective, as demonstrated by the strong correlations observed between sediment characteristics and radiological indices. The consistency between LLW sediment radioactivity patterns and regional geological characteristics suggests that wetland sediments can serve as reliable indicators of regional radiological conditions (Zorer et al., 2019; Caridi et al., 2021).

While the current radiological indices remain below regulatory limits, the spatial variations and environmental influences highlight the importance of continued monitoring, particularly in areas with high fine sediment accumulation or organic matter content (Zorer et al., 2019). The strong correlations identified between sediment properties and radionuclide distribution provide a clear framework for optimizing future monitoring programs. Specifically, monitoring can be made more efficient and cost-effective by (1) focusing sampling efforts on depositional zones with high fine particle and organic matter content, as these were identified as hotspots for radionuclide accumulation; (2) employing sediment grain size and organic matter content as rapid screening tools to guide targeted radiological analysis; and (3) scheduling monitoring campaigns to account for seasonal hydrological variations that affect sediment transport and deposition. The integration of these findings into wetland management practices can enhance both environmental protection and resource utilization efficiency, especially in areas where sediment characteristics and hydrodynamic conditions suggest potential for radionuclide accumulation (El-Reef et al., 2010; Khan et al., 2023).

Limitations of the study

While this study provides the first detailed radiological investigation of sediments in the LLW, it is important to acknowledge its limitations to frame the scope of our findings. Firstly, our assessment focuses

exclusively on the sediment compartment; a more holistic radiological evaluation would require analyzing other environmental media, such as surface water, groundwater, and local biota. Secondly, this study represents a single point-in-time snapshot and thus does not capture potential seasonal variations in radionuclide concentrations or transport dynamics. Finally, while we have identified key sediment properties governing radionuclide distribution, we acknowledge that other complex processes contribute to the observed patterns. For instance, diagenetic processes within pore water, such as the enhanced mobility of ^{226}Ra under reducing conditions, and physical mixing from bioturbation by benthic organisms can alter the vertical and spatial distribution of radionuclides. A full understanding of these mechanistic interactions was beyond the scope of this baseline study. Therefore, addressing these limitations, by incorporating multi-media analysis, seasonal monitoring, and detailed biogeochemical process studies, presents clear and valuable directions for future research to build upon the crucial benchmark established in this work.

Conclusion

This study provides the first detailed post-operational radiological baseline and process-oriented investigation for the sediments of the Lungluan Wetland, a critical ecosystem adjacent to the Maanshan NPP. Our findings confirm the absence of anthropogenic contamination (^{137}Cs) and reveal that the distribution of natural radionuclides is systematically governed by sediment properties and wetland hydrodynamics. Specifically, fine-grained particles (clay) and organic matter serve as primary sinks, creating predictable radioactivity hotspots in low-velocity depositional zones. All radiological hazard indices were well below safety limits, indicating no current risk to the public or the environment.

Critically, this research establishes a robust benchmark essential for assessing environmental changes during and after the NPP's decommissioning. The strong, predictable correlations between sediment characteristics and radionuclide levels offer a practical and cost-effective framework for optimizing future monitoring strategies by targeting areas with high

fine particle and organic matter content. Building on this baseline, future research should prioritize: (1) investigating seasonal dynamics and long-term accumulation trends to capture temporal variability; (2) applying specific activity ratios, such as $^{226}\text{Ra}/^{228}\text{Ra}$ to further elucidate geochemical processes and sediment transport pathways; and (3) developing integrated predictive models that incorporate sediment properties to enhance the efficiency of environmental assessments.

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Data availability The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication All authors have given their consent for publication.

Competing interests The authors declare no competing interests.

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