Oceanological and Hydrobiological Studies

International Journal of Oceanography and Hydrobiology

Volume 52, No. 2 June 2023
pages (147-165)

sciendo

ISSN 1730-413X
eISSN 1897-3191

Biomonitoring of radioactive contamination using benthic invertebrate communities in Manzala Lake, Egypt

by

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DOI: **https://doi.org/10.26881/oahs-2023.2.02**
Category: **Original research paper**
Received: **December 7, 2022**
Accepted: **March 2, 2023**

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Abstract

Manzala Lake, the largest in Egypt's Nile Delta, has significant human activity. The Lake's ecological condition has recently been impacted by a significant increase in agricultural, industrial, and urban wastewater discharge. A valuable tool for monitoring the water quality of Manzala Lake is the sensitivity of invertebrate species to various types of pollution, such as radioactive contamination. Activity concentrations of radionuclides Radium-226 (^{226}Ra), Thorium-232 (^{232}Th), Potassium-40 (^{40}K), and Caesium-137 (^{137}Cs) were measured in water, sediments and benthic invertebrate samples in 2020. The benthic community's spatial distribution and the radionuclides' bioaccumulation were evaluated to determine possible relationships. Thirty taxa of benthic invertebrates were recognised. The data illustrated that the mean activity concentration of radionuclides in water was in the order of ^{40}K > ^{232}Th > ^{226}Ra > ^{137}Cs, which changed into ^{40}K > ^{226}Ra > ^{232}Th > ^{137}Cs in the sediment and benthic invertebrates. Gastropoda and Ostracoda are the dominating groups of benthos in the lake and are related to the highest concentrations of radionuclides. The benthos species with shells dominated at the sites with the highest activity concentration of ^{226}Ra, while soft-bodied organisms dominated in sites with the highest average ^{137}Cs activity in these samples.

Key words: Manzala Lake, benthic invertebrate, radionuclides, concentration factor

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1. Introduction

Lake ecosystems are essential for aquatic species and human requirements, and environmental quality or water renewal rate changes have large-scale ecological and social consequences (Vincent 2009, Imam et al. 2020). Many pollutants, including radioactive elements, move through numerous chemical and biological cycles and end up in lakes (El-Reefy et al. 2010). Natural radionuclides have been a part of the earth since its inception. They are frequently dispersed across air, water, sediment, fauna, flora, and environments and contain Uranium-238, Thorium-232 radioisotopes, and Potassium-40 (Degerlier et al. 2008).

Natural radionuclides (^{238}U, ^{232}Th, and ^{40}K) and artificial radionuclides (^{137}Cs) are the two sources of radioactivity that are known to exist in the aquatic environment (Polykarpov 1966, Shannon and Cherry 1967). These radionuclides are critical elements that bioaccumulate in the tissues of aquatic organisms in diverse ways (Carvalho 2018). Consequently, these radionuclides enter the food chain by being ingested by marine life. The accumulation of these substances in the aquatic environment raises numerous concerns for the safety of critical organisms, the food chain, and, subsequently, humans (Carvalho et al. 2011). A valuation of radionuclide concentrations in aquatic organisms must be achieved to measure the intake of radionuclides by humans. Baseline records of radiation doses can be used to control any increase from agricultural or industrial actions (Feroz Khan et al. 2014). Several scientific studies have confirmed the presence of radionuclides in the marine environment, including aqueous media and biota (El-Reefy et al. 2010, Ibrahim and Ramzy 2013, Basha et al. 2013, Darwish et al. 2013, Hurtado-Bermúdez et al. 2019). The results of environmental monitoring programs of radionuclide concentrations have been compared with guidelines or environmental regulations to determine the relative attribution of potential sources and recognise human health risks regarding the methods of seafood consumption of the general public (Chambers et al. 2003, Ryan et al. 2003). Radioactive isotopes have been observed in aquatic ecosystems (aqueous media, fauna, and flora) throughout the food chain and in tissue absorption (Bahromovich et al. 2019).

Benthic invertebrates have been widely used to assess radionuclide contamination because they are relatively sedentary and inhabit diverse trophic groups (Burger et al. 2007, Li et al. 2020). Most benthic invertebrates are found in sediments and are an important route for transferring pollutants to higher species, such as fish or birds (Pastorino et al. 2020). The dietary status and pollution level are the most significant factors regulating the zoobenthos community (Cai et al. 2011). Radioactive pollution in aquatic ecosystems is one of the most hazardous anthropogenic influences on the biota. Studying the response association between benthic communities and radionuclides provides vital information for interpreting cumulative effects. It also elucidates the passage of radionuclides up food chains and their fluxes in aquatic systems. Radionuclides can accumulate in the tissues of marine species and be passed up the food chain, exposing the organisms to ionising radiation that can affect individuals, communities, and ecosystems (Real et al. 2004, Carvalho et al. 2011). Thus, information on the concentrations and distributions of radionuclides in different samples is critical for environmental pollution, and its impact on human health is linked to natural radioactivity monitoring. Only a few studies exist on radioactive pollution in Manzala Lake (Yousef and Magdy 2017, Mitwalli et al. 2022) and the transmission of radionuclides into the biota.

The objective of this study is to investigate the main radionuclide concentrations in water, sediments, and benthic invertebrates, and the radioactive contamination of Manzala Lake and assess the activity concentration of ^{226}Ra, ^{232}Th, ^{40}K, and ^{137}Cs. In addition, the effect of radionuclide isotopes on the distribution of benthic invertebrates will be investigated, and the concentration factor (CF) will be determined.

2. Materials and methods

2.1. Study area

Manzala Lake is located on the northeastern coast of Egypt and is considered the largest lake in Egypt (Fig. 1). The lake lies between 31°45', 32°15' E and 31°00', 31°35' N with an area of approximately 52611 ha. It extends along the Mediterranean Sea, separated from the sea by a sandy margin, except at three outlets that supply the lake with saline seawater from the Mediterranean Sea. These outlets allow the movement of organisms between the lake and the sea: Boughaz El-Gamil, Boughaz El-Boughdady, and Boughaz New El-Gamil (Abdel Mola and Abd El-Rashid 2012). Manzala Lake has been exposed to various threats in the past six decades, chiefly from agricultural drainage, sewage, and industrial wastes. Annually, it receives approximately 650 and 1.7 million m^3 of untreated sewage water from Bahr El-Baqar and Hadous Drains, respectively. It also receives the industrial discharge

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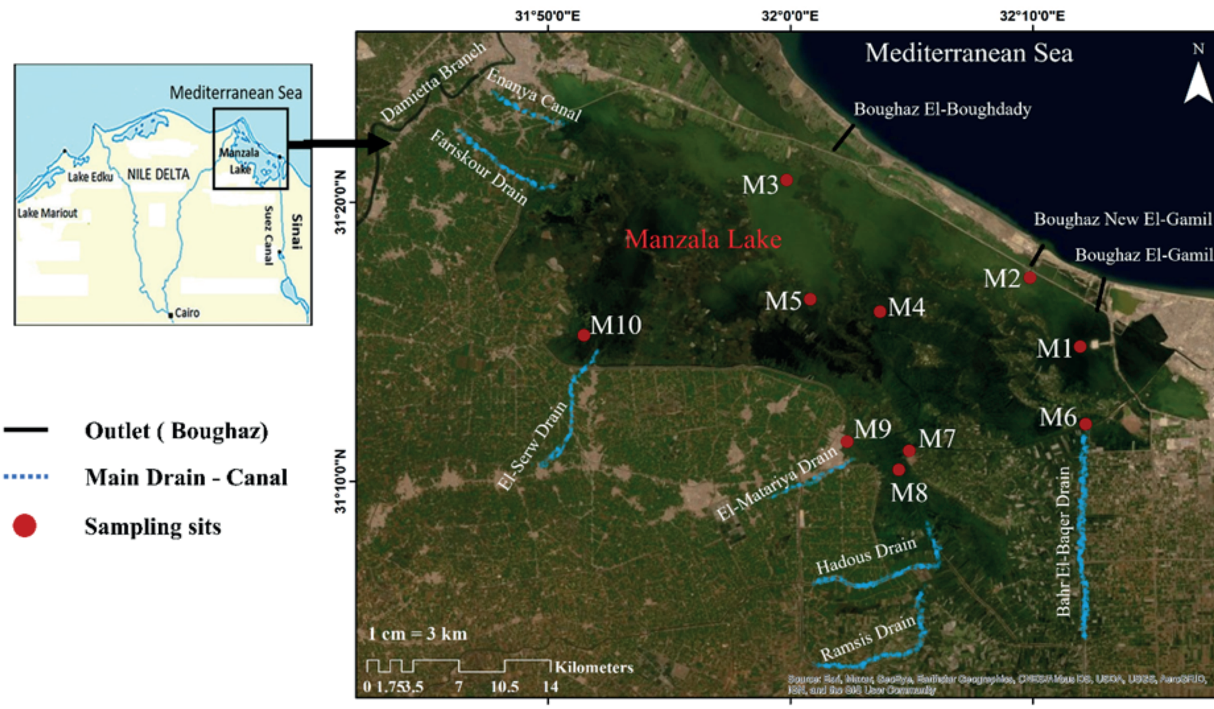

Figure 1

Map of the study area indicating the sampling sites in the Manzala Lake

from Industrial Compound in Port Said City. Freshwater (mainly from agricultural drainage) flows yearly into Manzala Lake from the main drains and canals (Faraskur, El-Serw, Matariya, Ramsis, Hadous, and Bahr El-Baqar) (Elshemy et al. 2016). A large amount of wastewater is transported into the lake from a heavily populated area of the Eastern Delta (Qalyubia, Sharkia, Ismailia, and Port Said Governorates), which significantly contributes to the deteriorating water quality of the lake (Zahran et al. 2015).

2.2. Sampling and samples preparation

Samples were collected from ten sites (M1–M10) during the winter and summer of 2020 (Fig. 1, Table 1). The three samples were taken from each site to represent that specific location. M1, M2, and M3 are influenced by seawater, sewage from the El-Gamil, New El-Gamil, and El-Boughdady outlets, and the Alhuria drain. Various sewage discharges influence M6 and M7 from the Bahr El-Baqar drain. M8 is affected by sewage and agricultural discharges from the new Bahr El-Baqar, and the Hadous and Ramsis drains. Agricultural emissions from the El-Matariya drain influence M9. M10 is affected by agricultural layoffs from the Inania, Faraskur, and El-Serw drains. Direct discharges do not influence M4 and M5.

Water samples were collected with a water sampler and placed in plastic bottles (2 l). Water temperature (°C), pH, total dissolved solids (TDS), water transparency (cm), and dissolved oxygen (DO) were measured, as discussed in the American Public Health Association-defined methods (APHA 2005) (supplementary information [SI]). The sediment and benthos were sampled using an Ekman grab sampler with a sample area of 225-cm^2 (15 × 15 cm) and separately packed in plastic bags. All samples were preserved in an icebox until they were placed in the lab. In the lab, the benthos samples were sieved using a net with a mesh diameter of 500 μm. The reserved materials were individually preserved in labeled bottles with 10% formalin. The samples were sorted in the laboratory, and the spotless benthic invertebrates were fixed with 75% ethanol. Relevant identification guides were used to identify the species or genus-level specimens (Day 1956, Walker 1959, Brinkhurst, and Jamison 1971, Flemming 1983, Brown et al. 1984, Hussein et al. 1988, Ibrahim et al. 1999). The sediment and benthos samples were dehydrated in an air-circulated oven at 74°C. The dried samples were weighed and crushed.

2.3 Gamma-ray spectrometry

Gamma spectrometry based on a high-purity germanium (HpGe) detector was used to determine

Table 1

Site descriptions, coordinates, and the nearest discharge source of the selected sites in Manzala Lake

Site	Site description	Nearest inputs	Source of discharge	Latitude	Longitude
M1	In front of Boughaz El-Gamil	El- Qabuty El-Gamil Alhuria-Port Said	seawater seawater sewage	31.247127° N	32.199660° E
M2	In front of Boughaz New El-Gamil	El- Qabuty El-Gamil Alhuria-Port Said	seawater seawater sewage	31.288324° N	32.164858° E
M3	In front of Boughaz El-Boughdady	the El-Dibah Enania Canal	seawater agricultural waste	31.346610° N	31.997482° E
M4	Middle of the lake	Indirect discharge		31.268021° N	32.061836° E
M5	Middle of the lake	Indirect discharge		31.275370° N	32.013763° E
M6	Bahr El Bashtir 1, in front of Bahr El-Baqer Drain	Bahr El-Baqer Drain	various waste	31.200735° N	32.203058° E
M7	Bahr El Bashtir 2, in front of the new Bahr El-Baqer Drain, south of the Lake	New Bahr El-Baqer Drain	various waste	31.184773° N	32.081840° E
M8	At the discharge point, Hadous and Ramsis Drains	Hadous Drain Ramsis Drain	agricultural waste agricultural waste	31.173402° N	32.074642° E
M9	In front of the El-Matariya Drain	El-Matariya Drain	agricultural waste	31.190334° N	32.039202° E
M10	In front of the El-Serw Drain	El-Serw Drain	agricultural waste	31.253946° N	31.858180° E

the specific activity concentration of natural and artificial radionuclides. The detector, coupled to standard electronics attached to a multichannel analyser card (MCA) installed in a PC, has a relative efficiency of approximately 50%, compared with the 3 × 3 NaI(Tl) detector. The detector was protected using a lead liner (10 cm thick) covered with a 2 mm copper foil. Data and spectrum analysis were performed using the ORTEC software MAESTRO. The energy calibration of the spectrometer was performed with point sources ^{241}Am (59.6 keV), ^{137}Cs (661.6 keV), and ^{60}Co (1172 and 1332.3 keV). For the spectrometer efficiency calibration, three well-known reference materials (RGU-1, RGTh-1, and RGK-1) were applied (IAEA 1987, Anjos et al. 2005, El Aassy et al. 2012). The water, sediment, and benthic invertebrate samples were placed in Marinelli beakers pre-dried and washed with dilute H_2SO_4 to avoid contamination. The Marinelli beakers were firmly closed for at least 4 weeks to ensure that the levels of Ra and their daughters were in secular equilibrium. For the sediment and benthic invertebrate samples, the specific activity concentration of radionuclides is expressed as Bq kg^{-1}; for the water samples, Bq l^{-1} is used. The time accumulation of the spectra was at least 48 h, depending on the activity of the samples. The activity concentration of ^{226}Ra (^{238}U-series) was determined via gamma-energy lines of 295.2 and 351.9 keV for ^{214}Pb and 609.3 and 1120.3 keV for ^{214}Bi. The gamma-energy lines of 338.4 and 911.2 keV for ^{228}Ac, 583 and 2614.4 keV for ^{208}Tl, and 727.3 keV for ^{212}Bi were used to represent the activity concentration of the ^{232}Th series. The activity concentration of ^{40}K and ^{137}Cs was determined via gamma lines of 1460.8 and 661.7 keV, respectively (Chieco et al. 1990). The activity concentration of the radionuclides was calculated using the reported equation (El Afifi et al. 2006).

The precision and accuracy of the analytical results provided in this study were verified using quality control procedures in IAEA reference materials (IAEA-414, IAEA-446). Using the equation proposed by Rihs and Condomines (2002), the uncertainty of the radionuclide concentration in samples with gamma spectrometry was calculated, and the confidence interval for counting instruments was 90%. The detector's lower limits of detection (LLDs) were required to estimate a minimum detection level for the radionuclides in each sample. The LLDs were defined by Imtiaz et al. (2005). The LLD values obtained for the sediment were 9.35, 0.45, 1.34, and 0.2 Bq kg^{-1} for ^{40}K, ^{226}Ra, ^{232}Th, and ^{137}Cs, respectively, and those for water were 0.84, 0.1, 0.1, and 0.02 Bq l^{-1}.

2.4 Statistical analysis

The ordinary index of benthic species richness (SR), the diversity index (H'), and evenness or equitability (E) were calculated for all the sampled sites using the Primer software (version 5) (Clarke and Gorley 2006). Hierarchical cluster analysis (CLUSTER) was performed to analyse the community structure using PC-ORD 5.0. Redundancy analysis (RDA) was employed to study the benthic invertebrate species in relation to the environmental and radioactive element variables. RDA was appropriate for data analysis as in the preliminary detrended correspondence analysis; the length of the gradient for the first axis was 2.33 SD < 3 SD (Lepš and Petr Smilauer 2003). Log transformation was performed to standardise the parameters before the examination. Monte Carlo permutation test parameters were set to 999 permutations to identify the significant environmental and radioactive element variables influencing the abundance and distribution of the benthic invertebrates ($p < 0.05$). The RDA was conducted using the Canoco 4.5 software (Ter Braak and Smilauer 2002).

3. Results and discussion

3.1. Environmental variables

The environmental parameters of water samples in Manzala Lake are shown in Table 2. The annual average water temperature fluctuated from 15.6°C in winter to 32.4°C in summer, with averages of 16.27 and 31.17°C during winter and summer, respectively. The pH of the Manzala Lake was alkaline, ranging from 7.56 to 8.97, with averages of 8.27 and 8.29 during winter and summer, respectively. The water transparency fluctuated between 10 and 70 cm. The lowest value (10 cm) was recorded at stations M6 and M9 during winter, whereas the maximum value was recorded in the east-west of the lake. The DO results showed a wide variation, with decreased DO in the southern section due to the effect of drains. Station M6 exhibited a noticeable impact of domestic waste from the Bahr El-Baqar drain, indicating a complete DO depletion in summer, and low DO (0.7 mg l^{-1}) in winter. Conversely, the maximum value was 14.7 mg l^{-1}, recorded at station M1 during the summer. The water salinity ranged from a relatively high 21.9% at station M3 (Boughaz El-Boughdady) to a relatively low 1.25% at station M8 (Mahmoud et al. 2020).

Regarding Manzala Lake, the salinity fluctuated substantially during recent decades, with the average value reported (17.24) in 1967 declining to (5.37) in 1975, and (2.53) in 2001, before progressively increasing to 4.26 in 2015 and 5.02 in 2020. Although prior studies found substantial geographical variability in DO levels, the lake is typically oxygenated, except for places near the inlets of diverse wastewaters, where the DO is fully depleted (Table S1). Long-term variations in the physicochemical properties of Manzala Lake water revealed the spatial and temporal variances in most parameters based on the quantity and quality of the various wastes discharged into the lake and the amounts of seawater that enter the lake through boughazes.

3.2. Benthic abundance and distribution

We recognised 30 taxa of the benthic invertebrates across all the sampling sites (Table S2, Fig. 2): six Arthropoda species (48%), seventeen Mollusca species (43%), and seven Annelida species (9%). The total average abundance of benthic invertebrates was 4330 ind. m^{-2}. Abdel Gawad et al. (2012) recorded 19

Table 2

The environmental parameters of water samples in Manzala Lake (Source: Mahmoud et al. 2020)

	Temp (°C)		pH		Trans. (cm)		DO (mg l^{-1})		TDS (mg l^{-1})	
	winter	summer	winter	summer	winter	summer	winter	summer	winter	summer
M1	15.6	32.34	7.93	8.89	35	20	5.04	14.7	2.905	4.69
M2	16.3	32.36	8.6	8.67	12	25	9.47	11.8	4.788	14.567
M3	16.8	32.28	8.4	8.5	12	35	6.96	7.5	8.981	21.903
M4	16.2	32.32	8.89	8.93	15	20	11.85	13.59	4.396	2.7041
M5	16.2	32.45	8.97	8.66	15	30	14.06	7.35	4.515	6.062
M6	16.9	29.22	7.62	7.62	10	12	0.7	0	2.618	2.2246
M7	16.6	29.28	8.12	7.91	20	23	9.8	1.63	3.255	2.3534
M8	16.2	29.5	7.72	7.56	15	23	1.6	0.44	2.625	2.5277
M9	16.3	30.33	7.93	7.68	10	67	6.34	12.5	1.393	1.1676
M10	15.6	31.65	8.5	8.52	15	20	8.9	5.55	1.743	4.9602
Min	15.6	29.22	7.62	7.56	10	12	0.7	0	1.393	1.1676
Max	16.9	32.45	8.97	8.93	35	67	14.06	14.7	8.981	21.903
Mean	16.27	31.173	8.268	8.294	15.9	27.5	7.472	7.506	3.7219	6.3159
StDev	0.435	1.417	0.475	0.542	7.34	15.2	4.24	5.55	2.174	6.68

taxa for benthic invertebrates in Ashtum El-Gamil, Lake Manzala, where Mollusca was the largest group, forming approximately 68.5% of the total population density of benthic invertebrates, followed by Arthropoda and Annelida. Fishar et al. (2015) identified nineteen macrobenthos species from the Mollusca, Annelida, and Arthropoda groups. The maximum number of species was reported for Mollusca, while Annelida and Arthropoda had the lowest number of species. El Komi (2021) also recorded 16 species of benthic communities in Lake Manzala. He stated that Ostracoda was the most numerous species found in the lake's sandy bottom sediments and was reported at most sample locations. The highest (22 species, 4823 ind. m^{-2}) and lowest (17 species, 3838 ind. m^{-2}) abundances and species numbers were recorded in the winter and summer, respectively. Arthropoda comprised one Insecta and five Crustacea; it recorded the highest average density and lowest number of species (2056 ind. m^{-2}, six species). This high density was due to the dominance of one species (Ostracods sp.) that accounted for 1038 ind. m^{-2}. It constituted 24% of the study area's population, which agrees with El Komi (2021). Abdel Gawad et al. (2012) stated that Ostracoda dominated the meiofauna in Lake Manzala and exhibited the highest peak in summer. Freshwater and marine mollusk species were included in the present investigation. It comprised three Bivalvia and fourteen Gastropods and recorded the highest species number and second highest density (17 species, 1866 ind. m^{-2}). *Gyraulus ehrenbergi* was the dominant species of molluscs (43%). Annelida comprised three Polychaeta and four Clitellata and had the lowest density (408 ind. m^{-2}). M3 In Lake Manzala recorded the highest density and diversity of species (13 species and 13089 individuals m^{-2}). M7 had the highest SR (1.5) and the highest H '(2), while M6 had the lowest SR (0.18) and the lowest H '(0.3). There was a noticeable decrease in the number of species (2 species) and individuals (275 individuals m^{-2}) at M6. The results showed that the study area recorded a widespread oxygen variation representing high hypoxia at M6. DO is an essential vital biotic impact on the aquatic ecosystem. The solubility and availability of nutrients are affected by DO, which releases nutrients from sediments accelerated under hypoxia, thereby influencing production in aquatic ecosystems (Abdelmongy and El-Moselhy 2015). At M8, the number of species was reasonably high, with *Gyraulus ehrenbergi* constituting 62% of the total individuals. Therefore, the minimum evenness (E = 0.53) of M8 was mainly due to the unequal distribution of individuals among the species (Table 3). The CLUSTER results showed that the sites could be

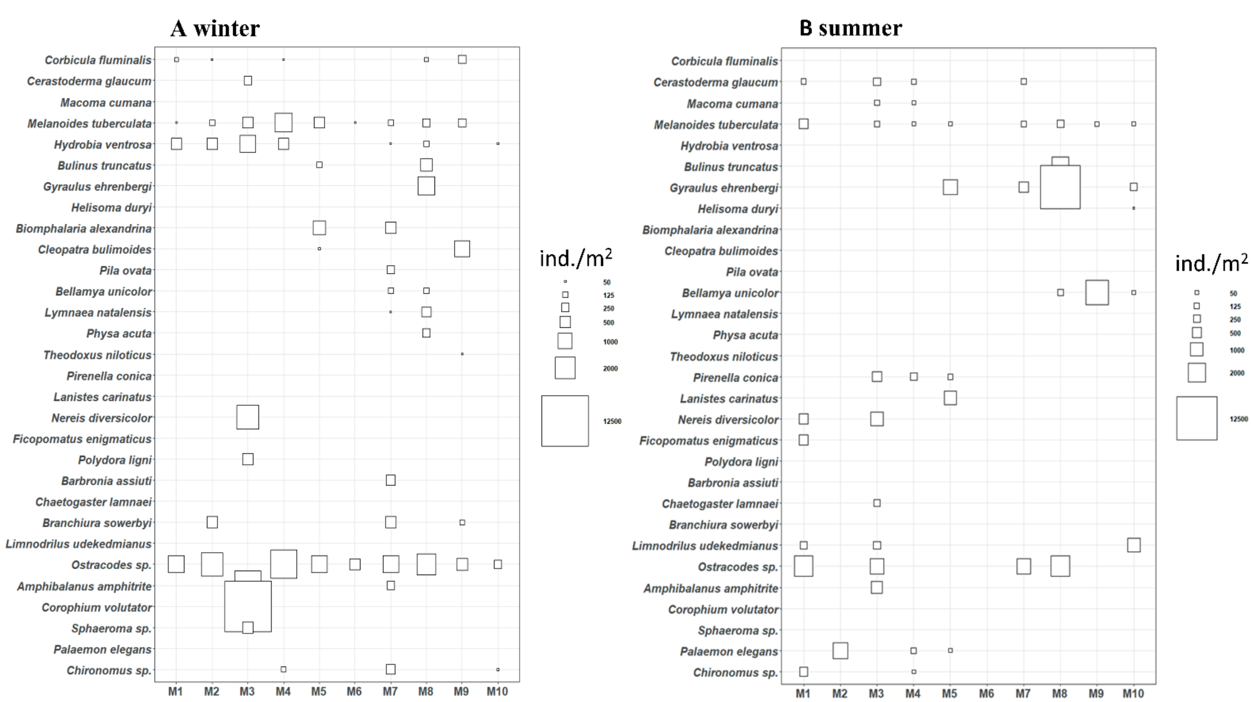

Figure 2

Taxa distribution within the Manzala Lake in (A) winter and (B) summer. The size of the squares is proportional to the density (the bigger squares, the higher density).

divided into four groups (Fig. 3). Group 1 comprised M1, M2, and M4; group 2 represented only M3 (in front of Boughaz El-Boughdady) because the number and abundance of its marine origin species was greater than other sites; group 3 included M5, M7, M8, and M9; and group 4 included M6 and M10. Group 1 is the northern section of the lake and is categorised by a high abundance of Arthropoda and marine species. Contrarily, group 3 is the southern section of the lake and is categorised by the high diversity and density of Mollusca. Hussein et al. (2011) stated that freshwater snails show a high degree of tolerance and plasticity in a specific range of physicochemical variation. Group 4 exhibited the lowest benthos density, owing to high sewage contamination and agricultural discharge from the Bahr El-Baqar and El-Serw drains.

3.3 Spatial and temporal variation of radionuclides in Lake Manzala

3.3.1 Radioactivity concentration in surface water

The spatial and temporal variation of the radionuclides (^{226}Ra, ^{232}Th series, ^{40}K, and ^{137}Cs) in the water samples are shown in Tables 4 and 5 and Figure 4 for the two seasons. The mean ^{226}Ra concentrations were 1.22 ± 0.14 and 1.34 ± 0.16 Bq l^{-1} ranging between 0.70 ± 0.08 and 1.72 ± 0.20 Bq l^{-1}. The concentration of ^{232}Th varied from 0.90 ± 0.19 to 2.01 ± 0.31 Bq l^{-1} with mean values of 1.42 ± 0.23 and 1.39 ± 0.22 Bq l^{-1}; the mean values of ^{40}K were 6.55 ± 0.78 and 7.20 ± 0.86 Bq l^{-1}, which varied between 3.12 ± 0.30 and 10.78 ± 1.36 Bq l^{-1}, while the values of ^{137}Cs ranged from 0.12 ±

Table 3

Population density (ind. m^{-2}), species number (sp. m^{-2}), species richness (SR), equitability (E), and the diversity index (H') benthic invertebrates in the investigated stations

	Station									
	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10
Total individuals m^{-2}	3314	2588	13089	3263	2576	275	2927	11303	3114	863
Total species m^{-2}	9	6	13	9	9	2	13	9	7	8
(SR)	0.99	0.64	1.27	0.99	1.02	0.18	1.50	0.86	0.75	1.04
(E)	0.69	0.72	0.67	0.58	0.82	0.44	0.78	0.53	0.63	0.65
(H')	1.53	1.30	1.71	1.28	1.80	0.30	2.00	1.17	1.23	1.35

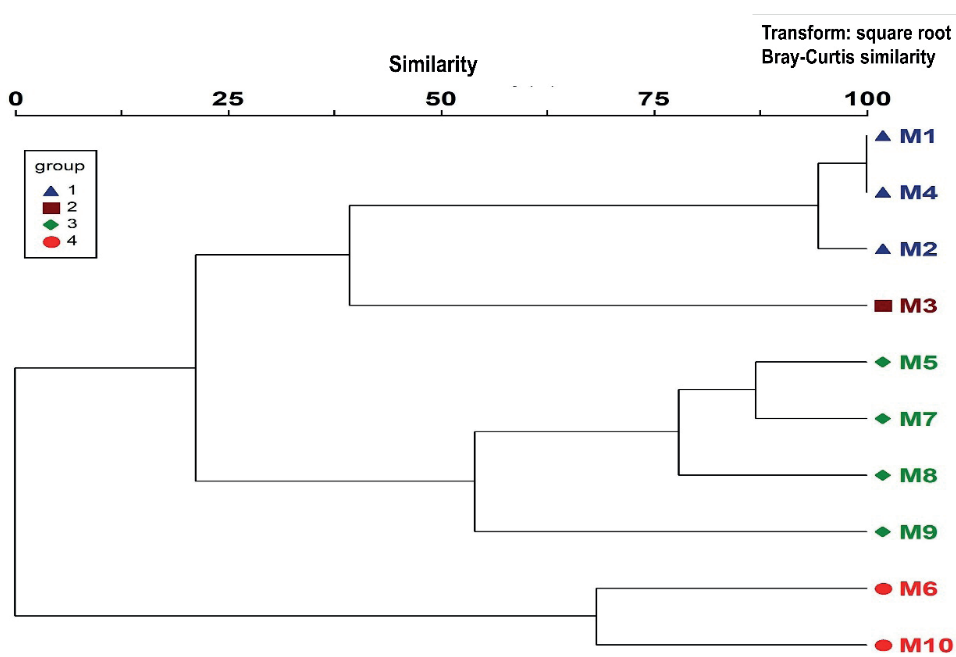

Figure 3

The dendrogram of hierarchical clustering (CLUSTER) using average group abundance of each sampling site

Table 4

The activity concentrations of radionuclides in water (Bq l^{-1}), sediment, and benthic invertebrates (Bq kg^{-1}) during the winter season in Manzala Lake

	^{226}Ra	^{232}Th	^{40}K	^{137}Cs (mBq l^{-1})	^{226}Ra	^{232}Th	^{40}K	^{137}Cs	^{226}Ra	^{232}Th	^{40}K	^{137}Cs
Sites	water				sediment				benthic invertebrates			
M1	0.89 ± 0.09	1.72 ± 0.26	6.75 ± 0.84	0.59 ± 0.04	32 ± 2.50	25.20 ± 2.50	250.65 ± 10.50	4.28 ± 0.33	37.30 ± 2.62	25.66 ± 2.67	782.73 ± 18.13	4.20 ± 0.23
M2	1.02 ± 0.09	1.51 ± 0.16	5.25 ± 0.55	0.61 ± 0.05	33 ± 2.88	23.12 ± 2.88	210.41 ± 14.20	4.56 ± 0.39	39 ± 2.90	29.50 ± 2.30	790.80 ± 19.20	4.60 ± 0.31
M3	1.45 ± 0.26	1.61 ± 0.40	7.99 ± 1.55	0.65 ± 0.05	26 ± 1.47	13.00 ± 1.47	362.74 ± 9.00	5.32 ± 0.43	29.49 ± 1.92	27.38 ± 2.65	630.36 ± 13.66	3.80 ± 0.20
M4	1.32 ± 0.22	1.23 ± 0.33	3.13 ± 0.75	0.25 ± 0.03	29 ± 2.02	21.75 ± 2.02	348.72 ± 11.64	2.66 ± 0.20	41.78 ± 2.80	23.70 ± 2.72	713.51 ± 17.52	1.50 ± 0.10
M5	1.34 ± 0.10	1.20 ± 0.15	3.12 ± 0.30	0.21 ± 0.02	34 ± 2.63	15.71 ± 2.63	353.33 ± 14.25	2.28 ± 0.19	72.22 ± 2.65	34.72 ± 2.57	1219.74 ± 15.55	1.30 ± 0.10
M6	1.56 ± 0.19	0.92 ± 0.19	9.80 ± 1.24	0.15 ± 0.01	25 ± 1.54	15.09 ± 1.54	291.77 ± 8.29	1.24 ± 0.10	30.50 ± 2.50	32.60 ± 1.90	690.60 ± 14.60	1.30 ± 0.08
M7	1.52 ± 0.20	2.01 ± 0.31	4.79 ± 0.57	0.13 ± 0.01	37 ± 1.28	23.52 ± 1.28	325.50 ± 6.26	0.93 ± 0.05	35.26 ± 2.13	27.85 ± 2.47	592.82 ± 13.69	0.90 ± 0.07
M8	0.70 ± 0.08	1.65 ± 0.18	6.73 ± 0.70	0.20 ± 0.02	26 ± 1.76	15.01 ± 1.76	320.77 ± 9.91	1.05 ± 0.10	66.79 ± 6.95	40.23 ± 6.72	1085.66 ± 45.02	0.96 ± 0.08
M9	1.18 ± 0.11	1.09 ± 0.17	7.18 ± 0.72	0.26 ± 0.03	22 ± 1.66	30.38 ± 1.66	479.92 ± 11.41	1.33 ± 0.10	50.05 ± 2.34	32.90 ± 2.60	598.28 ± 13.18	1.40 ± 0.14
M10	1.19 ± 0.07	1.21 ± 0.10	10.72 ± 0.59	0.52 ± 0.04	30 ± 2.60	35.40 ± 2.60	490.10 ± 12.30	3.99 ± 0.29	49.80 ± 4.60	43.80 ± 5.50	1130.80 ± 32.40	3.50 ± 0.23
Mean	1.22 ± 0.14	1.42 ± 0.23	6.55 ± 0.78	0.36 ± 0.03	29.72 ± 2.03	21.82 ± 2.03	343.39 ± 10.78	2.76 ± 0.22	45.22 ± 3.14	31.83 ± 3.21	823.53 ± 20.29	2.35 ± 0.15

Table 5

The activity concentrations of radionuclides in water (Bq l^{-1}), sediment, and benthic invertebrates (Bq kg^{-1}) during the summer season in Manzala Lake

	^{226}Ra	^{232}Th	^{40}K	^{137}Cs (mBq l^{-1})	^{226}Ra	^{232}Th	^{40}K	^{137}Cs	^{226}Ra	^{232}Th	^{40}K	^{137}Cs
Sites	water				sediment				benthic invertebrates			
M1	0.98 ± 0.10	1.68 ± 0.25	7.43 ± 0.92	0.57 ± 0.04	41.60 ± 3.25	30.24 ± 3.00	325.85 ± 13.65	4.50 ± 0.35	48.49 ± 3.40	33.36 ± 3.47	861.01 ± 19.94	4.20 ± 0.19
M2	1.12 ± 0.10	1.48 ± 0.16	5.78 ± 0.61	0.59 ± 0.05	42.90 ± 3.74	27.75 ± 4.06	273.54 ± 18.46	4.80 ± 0.41	50.70 ± 3.77	38.35 ± 2.99	869.88 ± 21.12	3.90 ± 0.24
M3	1.60 ± 0.29	1.58 ± 0.39	8.79 ± 1.70	0.63 ± 0.05	34.26 ± 1.92	15.60 ± 1.63	471.56 ± 11.70	5.60 ± 0.45	30.37 ± 1.77	35.65 ± 2.64	738.20 ± 13.02	3.70 ± 0.24
M4	1.46 ± 0.24	1.21 ± 0.33	3.44 ± 0.82	0.24 ± 0.03	38.47 ± 2.63	26.10 ± 2.95	453.33 ± 15.13	2.80 ± 0.21	37.09 ± 2.60	36.12 ± 3.34	722.69 ± 18.52	1.50 ± 0.14
M5	1.47 ± 0.11	1.17 ± 0.14	3.43 ± 0.33	0.20 ± 0.02	44.90 ± 3.42	18.85 ± 1.95	459.33 ± 18.53	2.40 ± 0.20	80.93 ± 6.67	50.50 ± 6.35	1866.50 ± 46.90	0.96 ± 0.10
M6	1.72 ± 0.20	0.90 ± 0.19	10.78 ± 1.36	0.14 ± 0.01	32.51 ± 2.00	18.11 ± 1.51	379.30 ± 10.77	1.30 ± 0.10	39.65 ± 3.25	42.38 ± 2.47	759.66 ± 16.06	0.80 ± 0.05
M7	1.67 ± 0.22	1.97 ± 0.30	5.27 ± 0.62	0.12 ± 0.01	48.10 ± 1.66	28.23 ± 1.36	423.15 ± 8.13	0.98 ± 0.05	45.83 ± 2.77	36.21 ± 3.22	652.10 ± 15.05	0.70 ± 0.05
M8	0.77 ± 0.08	1.62 ± 0.18	7.40 ± 0.77	0.19 ± 0.02	34.12 ± 2.28	18.02 ± 2.09	416.99 ± 12.88	1.10 ± 0.10	111.32 ± 8.13	68.59 ± 8.01	1532.97 ± 48.43	0.92 ± 0.10
M9	1.30 ± 0.12	1.07 ± 0.17	7.90 ± 0.79	0.25 ± 0.03	29.67 ± 2.16	36.46 ± 2.58	623.90 ± 14.83	1.40 ± 0.10	46.51 ± 4.36	44.02 ± 5.87	1043.92 ± 31.44	1.50 ± 0.14
M10	1.31 ± 0.08	1.18 ± 0.10	11.79 ± 0.65	0.50 ± 0.04	39.85 ± 3.38	42.48 ± 3.24	637.13 ± 15.99	4.20 ± 0.31	64.74 ± 5.98	56.94 ± 7.15	1243.88 ± 35.64	3.00 ± 0.19
Mean	1.34 ± 0.16	1.39 ± 0.22	7.20 ± 0.86	0.34 ± 0.03	38.64 ± 2.64	26.18 ± 2.43	446.41 ± 14.01	2.91 ± 0.23	55.56 ± 4.27	44.21 ± 4.55	1029.08 ± 26.61	2.12 ± 0.14

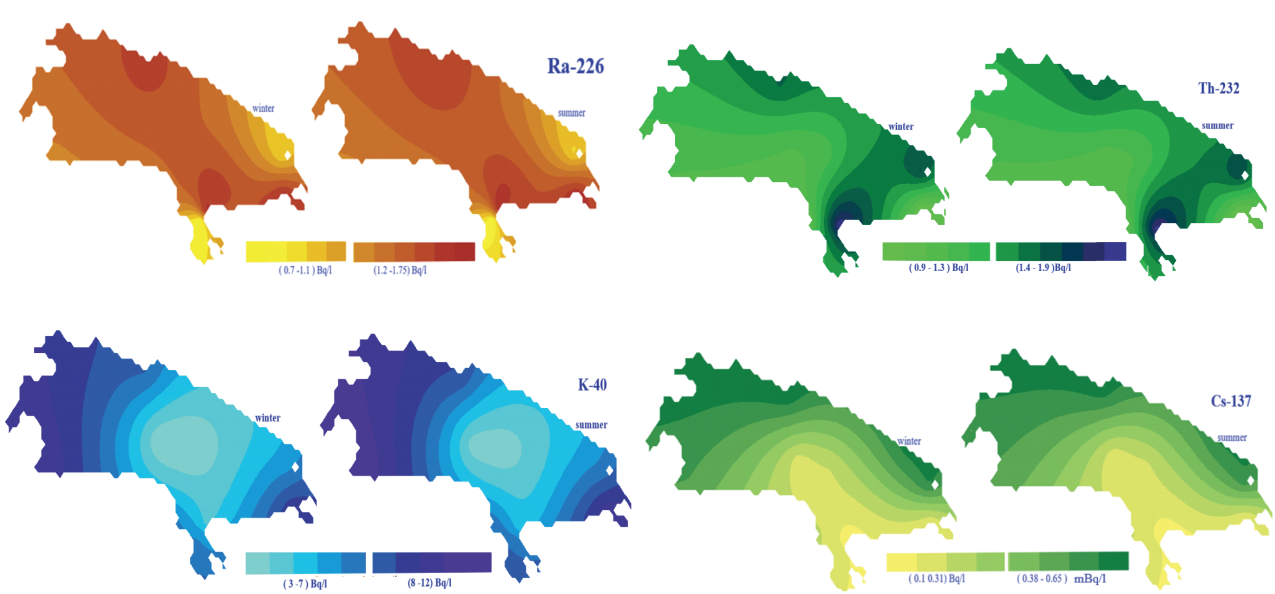

Figure 4

Contour maps of ^{226}Ra, ^{232}Th, ^{40}K, and ^{137}Cs activity concentration in water samples of Manzala Lake

0.01 to 0.65 ± 0.04 mBq l^{-1} with mean values of 0.36 ± 0.03 and 0.34 ± 0.03 Bq l^{-1} during winter and summer, respectively. The water sample results revealed that the spatiotemporal activity concentration of the radionuclides depended on different discharge sources, such as industrial, agricultural, and municipal wastewater. The data showed that the mean activity concentration was in the order of ^{40}K > ^{232}Th > ^{226}Ra > ^{137}Cs. The north and south areas of the lake at the Bahr El-Baqar drain exhibited the highest ^{226}Ra activity concentration for two seasons. This may be due to the agricultural waste in the north that contains superphosphate used as fertiliser. Furthermore, mixed waste (industrial, sewage, and agricultural) is discharged at the southern area of the lake. Superphosphate fertiliser and phosphogypsum are utilised in the area of the Nile Delta, leading to an increase in ^{226}Ra levels (Hussein and Ahmed 1997). The lowest levels were found in front of the Hadous and Ramsis drains and at the El-Gamil outlet east of the lake.

The distribution of ^{232}Th content in the water samples significantly differed from that of ^{226}Ra, and high values of ^{232}Th were primarily observed in the eastern and southern regions of the lake, which may have had an impact on the discharge of industrial waste (petroleum filtering and related chemical byproducts) (Barakat 2004). Moreover, a fairly high concentration of ^{40}K was measured in the northern part of the lake, primarily due to agricultural runoff and seawater inlets. Considering that seawater contains various cations of elements, this is the expected behavior of ^{40}K in lake water. There is a significant concentration of ^{40}K in saline water (Abdullah 2013). The variations in drainage water flow rates can drive the slight variation in 40K concentrations between seasons. The lowest concentrations of ^{40}K activity were observed in the middle of the lake.

The anthropogenic radionuclide ^{137}Cs was investigated, and its highest values were observed on the lakeshore closest to El Boughaz in the north of the lake. In contrast, its lowest values were observed in the southern part of the lake during two seasons. The ^{137}Cs activity in the water was probably attributed to the stability of Cs in dissolved form in the lake water. Most Cs compounds are soluble in water with chemical affinities similar to K's (UNSCEAR 1982). Manzala Lake water samples generally exhibit higher radioactive activity concentrations than are allowed under permissible drinking water limits (IAEA 2005).

3.3.2. Radioactivity concentration in sediments

The activity concentrations of ^{226}Ra, ^{232}Th series, ^{40}K, and ^{137}Cs in the sediment samples in Bq kg $^{-1}$ are shown in Tables 4 and 5 and Figure 5 for two seasons. The ^{226}Ra activity concentration fluctuated from 22 ± 1.66 (M9) to 37 ± 1.28 Bq kg^{-1} (M7) with a mean value of 29.72 ± 2.03 Bq kg^{-1} during winter. In summer, it ranged from 29.67 ± 2.16 (M9) to 48.10 ± 1.66 Bq kg^{-1} (M7) with an average value of 38.64 ± 2.64 Bq kg^{-1}. The ^{232}Th activity concentration varied from 13.00 ± 1.47 to 42.48 ± 3.24 Bq kg^{-1} with mean values of 21.82 ± 2.03 and 26.18 ± 2.43 Bq kg^{-1} during winter and summer, respectively. The concentration of ^{40}K ranged from 210.41 ± 14.20 and 291.77 ± 8.29 (M2) to 490.10 ± 12.30 and 637.13 ± 15.99 Bq kg^{-1} (M10) with mean values of 343.39 ± 10.78 and

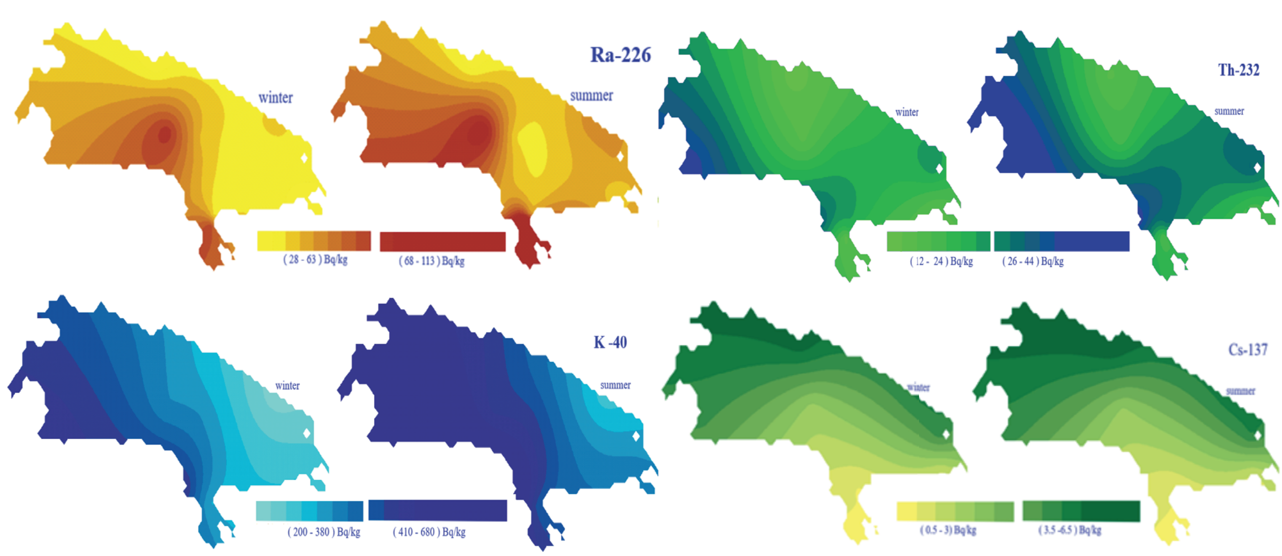

Figure 5

Contour maps of ^{226}Ra, ^{232}Th, ^{40}K, and ^{137}Cs activity concentration in sediment samples of Manzala Lake

446.41 ± 14.01 Bq kg^{-1} during winter and summer, respectively. The mean activity concentration of ^{137}Cs in the sediment was 2.76 ± 0.22 and 2.91 ± 0.23 Bq kg^{-1} during winter and summer, respectively. The findings indicated that the distribution of ^{226}Ra, ^{232}Th, ^{40}K, and ^{137}Cs in the sediment was not uniform and that radioactivity frequently fluctuated substantially, depending on the various sources of contamination. The order of the mean activity concentration was ^{137}Cs < ^{232}Th < ^{226}Ra < ^{40}K. The activity concentration of ^{232}Th was lower than those of ^{226}Ra and ^{40}K. The western and southern regions of the lake contained the majority of the radioactive concentrations with high levels. As mentioned, drains are predominant in the western and southern regions of Manzala Lake. The lake's northernmost area has the highest activity concentrations for ^{137}Cs. According to El-Reefy et al. (2010), water flowing into the lake from the Mediterranean Sea may increase the amount of ^{137}Cs in the sediment. The ^{137}Cs radionuclide bonds to mud minerals in the topsoil layers (Bourcier et al. 2011). The concentration and distribution of radionuclides in Manzala Lake vary and may be influenced by several factors, such as mixing processes, salinity, water flow dynamics, the shallowness of the lake, and natural and human activities. The mean activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K were within the UNSCEAR (2000) worldwide values for soil. However, it was slightly higher during the summer because of increased water discharge into Manzala Lake during the agricultural season.

3.3.3. Radioactivity concentration in benthic invertebrates

The activity concentrations of radionuclides in the benthos samples for two seasons are represented in Tables 4 and 5 and Figure 6. The ^{226}Ra and ^{232}Th activity concentration ranges were 29.49 ± 1.92 to 72.22 ± 2.65 and 25.66 ± 2.67 to 43.80 ± 3.21 Bq kg^{-1} and 30.37 ± 1.77 to 111.32 ± 8.13 and 33.36 ± 3.47 to 68.59 ± 8.01 Bq kg^{-1} during winter and summer, respectively. The ^{40}K and ^{137}Cs concentrations varied between 598.28 ± 13.18 and 1219.74 ± 15.55 and 0.9 ± 0.07 and 4.6 ± 0.31 Bq kg^{-1} and between 652.10 ± 15.05 and 1532.97 ± 48.43 and 0.7 ± 0.05 and 4.2 ± 0.19 Bq kg^{-1} during winter and summer, respectively. The highest activity concentration of ^{226}Ra, ^{232}Th, and ^{40}K was dominant at the southern part of the lake in front of the Hadous, Ramsis, El-Matariya, and El-Serw drains. This showed that the radionuclide concentration affects agricultural discharge. Mollusca and Ostracoda are the dominating groups of benthic invertebrates in the regions with the highest concentrations of radionuclides (^{226}Ra, ^{232}Th, and ^{40}K). Meiobenthic ostracod species do not have a planktonic stage and are constantly exposed to pollutants, and the meiofauna's rapid generation cycles and fast growth produce a considerably fast response to radioactive contaminants (Denis and Galtsova 2012). The variations in benthic invertebrate dominance and concentrations of radionuclides may be related to the environmental conditions of the various water bodies and the amount of suspended

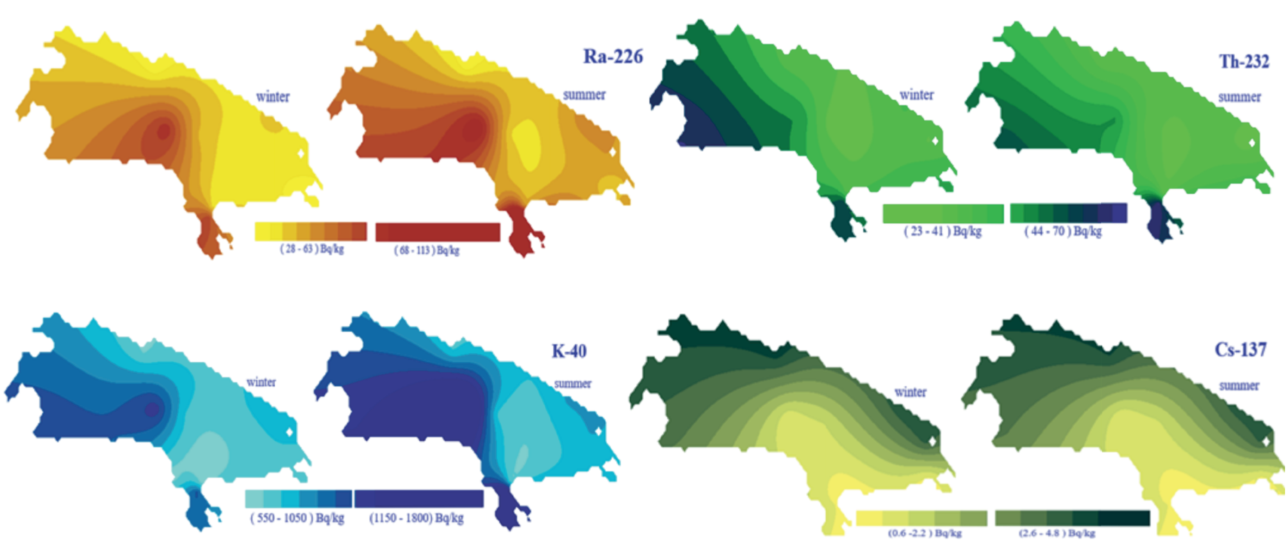

Figure 6

Contour maps of ^{226}Ra, ^{232}Th, ^{40}K, and ^{137}Cs activity concentration in benthos samples of Manzala Lake particulate matter discharged from different sources. Benthic invertebrate species with shells, such as Mollusca and Crustacea, were dominant at sites with the highest activity concentration of ^{226}Ra in these samples. These findings are consistent with Cherry and Shannon's (1974) and Davy and Conway (1974) findings. We hypothesised that aquatic invertebrates with shells increased the 226Ra activity concentration because 226Ra is known to follow the calcium mechanism during metabolism and accumulate in places where calcium is likely to be deposited, as suggested by Iyengar (1984) and Hameed et al. (1997).

Here, ^{232}Th had a low activity concentration, compared with ^{226}Ra and ^{40}K in the benthic invertebrates. Thorium minerals in natural waters dissolve significantly less than do uranium minerals. Although ^{226}Ra partially dissolves in water, a portion, along with clay and other sediments, precipitates at the bottom of lakes and reservoirs (Khasanov and Mavlonov 2019). According to a study (Chu, Wang 2000), Ra is similar to other alkaline earth metals in that it exists as Ra^{2+}, which is only moderately soluble in natural water. It may also sparingly precipitate soluble salts (sulfate, carbonate, and chromate). Benthic invertebrates have restricted mobility; therefore, they are benthic and grazer or filter feeders. They are model indicators because they can accumulate radionuclides several folds the concentration in aquatic ecosystems (Burger et al. 2007).

The activity concentration of ^{40}K was extremely high in all the stations during the two seasons. This may have been due to the excess of fertiliser used in the area around the lake, and most stations have numerous Molluscans and Crustaceans. Molluscans and Crustaceans naturally have a hard shell of calcium carbonate; the high percentage of calcium carbonate may have caused a high ^{40}K concentration in the examined samples. The activity concentration of ^{137}Cs in the sediment and benthic fauna samples increased in the northern part of the lake, which exhibited the dominant species belonging to marine Crustacea. Although detected at relatively low levels in the lake, the ^{137}Cs entering the sea due to fallout is traceable and indicative of the behavior of ^{137}Cs. These results correlated with those observed in seawater described by Othman and Mamish (1995) and Ammar et al. (2009).

The radioactive concentrations in the water, sediment, and benthic invertebrates of Manzala Lake were compared with those in different locations (Table 6). The mean activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K of water in this study were higher than those in Lake Nasser (Imam et al. 2020) and lower than those in the area of Marsa Alam-Shalateen, Egypt (Arafat et al. 2017) and Lake Qarun (Amin 2013). The activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in the sediment of this study were higher than those in the sediment from Manzala Lake (Mitwalli et al. 2022), Lake Nasser (Imam et al. 2020), Burullus Lake (El-Reefy et al. 2010), the Niger Delta flood plain lakes (Biseni) in Nigeria (Agbalagba and Onoja 2011) and the marine environment (Uddin et al. 2015). Additionally, the activity concentration of ^{232}Th in the sediment was

Table 6

Comparison of the activity concentrations of ^{226}Ra (U-238 series), ^{232}Th-series, ^{40}K and ^{137}Cs in water (Bq l^{-1}), sediment, and benthic invertebrates (Bq kg^{-1}) of Manzala Lake with different areas

Locations	^{226}Ra (U-238 series)	^{232}Th-series	^{40}K	^{137}Cs	Note	References
Manzala Lake	1.28 ± 0.15 34.18 ± 2.34 50.39 ± 3.7	1.41 ± 0.23 24 ± 2.23 38.02 ± 3.88	6.88 ± 0.82 394.9 ± 12.4 926.31 ± 23.45	0.35 ± 0.03 2.84 ± 0.23 2.28 ± 0.15	Water sediment benthic invertebrates	Present study
Lake Qarun, Egypt	6.4	3.2	31.3	-	Salt water	Amin 2013
Marsa Alam-Shalateen area, Red Sea coast, Egypt	< 0.7 - 6.31	< 0.6	< 3 to 38.17	-	Sea water	Arafat et al. 2017
Lake Nasser, Egypt	0.43 ± 0.08 26 ± 1.6	0.44 ± 0.1 19 ± 1.5	4.4 ± 0.93 255.6 ± 7.9	- -	Fresh water Sediment	Imam et al. 2020
Manzala Lake	20.2 (4.3-47.5)	14.8 (1.9-7.3)	285.8 (127.6 -409.1)	-	sediment	Mitwalli et al. 2022
Burullus Lake, Egypt	14.3	20	312	2.7-15.9	sediment	El-Reefy et al. (2010)
Niger Delta flood plain lakes (Biseni), Nigeria	25±4.4	22±4.4	220±63		sediment	Agbalagba and Onoja 2011
Marine environment, Kuwait	7.3–20.5	-	353–445	1.0–3.1	sediment	Uddin et al. 2015
Coast of Greater Accra, Ghana	22.04	108.60	29.78	-	Shore sediment	Amekudzie et al. 2011
Coastal Waters Syria	6.04	-	218.8	2.69	Mollusks	Ammar et al. 2009

lower than that of the Ghanaian Coast of Greater Accra (Amekudzie et al. 2011). Similarly, benthic invertebrates have higher mean activity concentrations of ^{226}Ra, ^{40}K, and ^{137}Cs than mollusks from waters along the coast of Syria (Ammar et al. 2009).

3.4 The CF of the radionuclides

The CF (Table S3), described as the ratio of the concentration of a contaminant substance in the organisms (Bq kg^{-1} wet weight) to the concentration in the surrounding water environment (Bq l^{-1}), first appeared in aquatic toxicology in (Rand 1995). It is necessary to quantify the active concentrations of radioactivity in ecosystems and biota to describe the intake and accumulation of radionuclides (Eisenbud and Gesell 1997). The range of CF values of ^{226}Ra in the benthic invertebrates varied (0.7×10^2 to 3.4×10^2 and 0.7×10^2 to 5.2×10^2 Lkg^{-1}), with average values of 1.5×10^2 and 1.7×10^2 Lkg^{-1} during winter and summer, respectively. The CF of ^{232}Th varied from 0.5×10^2 to 1.3×10^2 and 0.66×10^2 to 1.5×10^2 Lkg^{-1} with average values of 0.9×10^2 and 1.2×10^2 Lkg^{-1} during winter and summer, respectively. The highest CF of ^{40}K was 1.4×10^3 and 1.9×10^3 Lkg^{-1} at M5, with average values of 0.5×10^3 and 0.6×10^3 Lkg^{-1} during winter and summer, respectively. The CF of ^{137}Cs varied (0.2×10^2 to 0.31×10^2 and 0.2×10^2 to 0.26×10^2 Lkg^{-1}) with average values of 0.23×10^2 and 0.21×10^2 Lkg^{-1} during winter and summer, respectively. The reported values for ^{232}Th and ^{137}Cs were lower than the recommended values listed in the technical report on CFs in the marine environment (IAEA 2005). According to the IAEA, the permissible limits of CFs for ^{226}Ra, ^{232}Th, and ^{137}Cs were 0.65×10^2, 0.51×10^3, and 0.65×10^2 Lkg^{-1}, respectively. The CF for 226Ra exceeded the recommended level, indicating that Ra had accumulated to high levels in mollusk shells, which agreed with the finding in mollusks in certain locations along the coast of Syria (Ammar et al. 2009). The CFs in this study agreed with reported values (Holtzman 1966, Davy and Conway 1974, Iyengar 1990, Ammar et al. 2009). According to studies on freshwater environments, mollusks and crustaceans can accumulate Ra to different degrees (Hameed et al. 1997, Hosseini et al. 2008, Ammar et al. 2009).

3.5 Relationship between benthic assemblages and radioactive elements

The RDA results for benthic species and radioactive elements in the sediment (Fig. 7A) indicated that the first two ordination axes accounted for 22.2% and 13.8% of the variation in the benthic assemblages, respectively. The species-radionuclides correlations were as high as 0.903 for axis 1 and 0.977 for axis 2, which explained 44.8% and 27.6% of the cumulative variation in species and radionuclides, respectively. The total cumulative percentage of the relationship between species and radionuclides for the first two axes was 72.4%, demonstrating that the associations could be better reproduced using an ordination map (Table 3). According to the permutation test, the primary radioactive element that could affect the community structure of the benthic invertebrates in the study area was the ^{137}Cs radionuclide (F-ratio = 1.85, P-value = 0.012). The RDA results revealed a strong correlation between ^{137}Cs and Annelida species (*Nereis diversicolor*, *Limnodrilus udekedmianus*, and *Ficopomatus enigmaticus*), which was recorded in M1 and M2 that were influenced by seawater and sewage from the El-Gamil, New El-Gamil, and Alhuria drains. This may be because the soft tissues of the Annelida species absorbed the ^{137}Cs solute in the water, and ^{137}Cs is a radioactive element introduced into the lake via the sea. It is soluble in seawater and is mobile. The findings correlated with Saniewski et al. (2022), who indicated that organisms without shells (soft tissues) exhibited the highest average ^{137}Cs activity.

Moreover, annelids are deposit feeders, which are more accompanied by Cs uptake. Rowan et al. (2013) stated that ^{137}Cs concentrations in deposit-feeding benthic invertebrates were significantly greater in coastal biota and were highly connected with ^{137}Cs concentrations in associated sediments. *Corbicula fluminalis*, *Theodoxus niloticus*, and *Branchiura sowerbyi* strongly correlated with ^{232}Th. Mollusc species (*Gyraulus ehrenbergi*, *Biomphalaria alexandrina*, *Physa acuta*, *Bulinus truncates*, *Pila ovata*, and *Lymnaea natalensis*) exhibited a transparent relationship with ^{226}Ra and ^{40}K. The high abundance of these species at M8 and M7 indicated that they increase in polluted waters. Archna et al. (2015) stated that the genus *Physa*, which belongs to Pulmonata, is a biological marker of organic pollution and eutrophication. Furthermore, *Gyraulus* sp. dwelled in polluted waters (Gallardo and Prenda 1994). Additionally, these stations, located in the southern section of the lake, receive agricultural discharges containing phosphate fertilisers, which enhance the K and Ra levels (Hassan et al. 2016).

The RDA results for benthic species and radioactive and environmental variables in the water (Fig. 7B) illustrated that axes 1 and 2 constituted 31.5% and 15.1% of the total variation, respectively. TDS had significant effects on the distribution of marine arthropod species. Khalil (1990) and Abdel Gawad et al. (2012) stated that the species distribution and biodiversity in Manzala Lake are mainly defined by

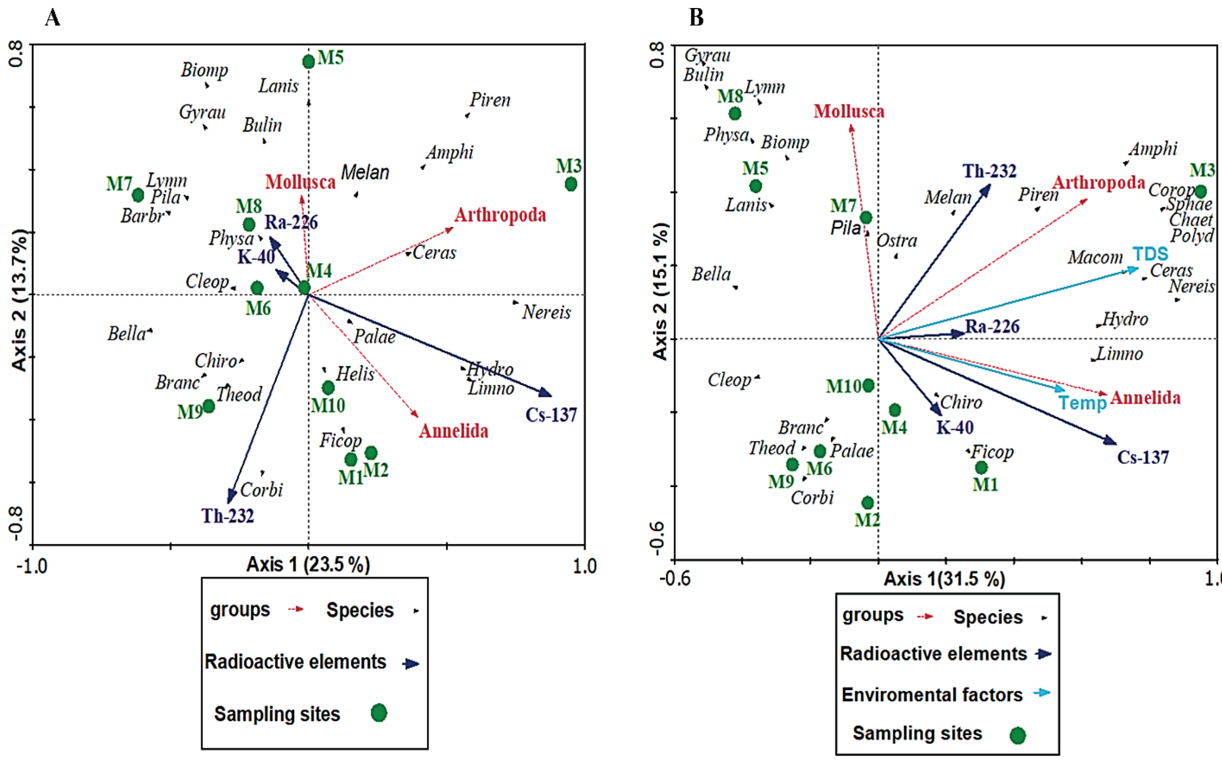

Figure 7

(A) RDA triplot illustrating associations between benthic invertebrate species and radioactive elements in sediment. (B) RDA triplot illustrating associations between benthic invertebrate species and radioactive elements in water and water quality variables. For acronyms, see supplementary data, Table S.

salinity. In addition, TDS is significant in explaining the population size and distribution. The water clarity has a considerable impact on available light, a crucial variable in the vertical distribution of benthos, a significant food source for many benthos groups (Denis and Galtsova 2012). *Pirenella conica* and *Melanoides tuberculate* exhibited a strong relationship with ^{232}Th. *Ficopomatus enigmaticus* indicated a clear relationship with ^{40}K. The strong correlation between ^{226}Ra, ^{232}Th, and TDS in water revealed the similarity of the chemical properties of Ra and Th. However, there was a difference in solubility; Ra and Th are highly insoluble in natural waters. Furthermore, a strong correlation existed between ^{40}K and ^{137}Cs, whereas living organisms accumulated Cs and K (Moon et al. 2021), which have similar chemical characteristics. In addition, ^{40}K has a higher solubility and is more mobile than the other radionuclides.

4. Conclusion

Bioindicators, one of several recent advancements in indirect environmental assessment techniques, have tremendous potential, considering that their biomass strongly tends to absorb particular radionuclides. In Manzala Lake, which is exposed to numerous anthropogenic challenges, benthic invertebrates are excellent candidates for monitoring the ecological conditions of the lake. The radioactivity levels of ^{226}Ra, ^{232}Th, ^{40}K, and ^{137}Cs were measured in water, sediments, and benthic invertebrate samples in Manzala Lake by gamma-ray spectrometry. The mean activity concentrations of ^{226}Ra, ^{232}Th, ^{40}K, and ^{137}Cs were 1.28 ± 0.15, 1.4 ± 0.23, 6.9 ± 0.82, and 0.35 ± 0.03 Bq l^{-1} in water; 34.4 ± 2.34, 24 ± 2.23, 394.9 ± 12.40, and 2.84 ± 0.23 Bq kg^{-1} in sediments; and 50.51 ± 3.7, 38 ± 3.9, 9926.31 ± 23.45, and 2.28 ± 0.15 Bq kg^{-1} in benthic invertebrates. The results indicated that a mixture of industrial, agricultural, and municipal wastewater effluents affected the concentration and distribution of radionuclides in Manzala Lake. Benthic invertebrate abundance varied noticeably between the sampling locations. A relatively high mollusk density was observed at the most ^{226}Ra and ^{40}K-contaminated sites (M7, M8, and M9), while a reasonably high annelids density was observed at the most ^{137}Cs radionuclide-contaminated sites (M1, M2, and M3).

Contrarily, a moderately low benthic invertebrates density was observed at the most ^{232}Th-contaminated sites (M6 and M10). In addition, the CF for ^{226}Ra demonstrated a high accumulation level in molluscan shells. The ^{137}Cs radionuclide was the principal radioactive element that could impact the community structure of benthic invertebrates in Manzala Lake. The main environmental factor determining the spatial distribution of benthic organisms was TDS. Considering these findings, this study recommends using other benthic fauna and aquatic species to monitor radioactive pollutants in aquatic ecosystems in Egyptian water.

Data availability

All data will be available from the corresponding author upon request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding

The National Institute of Oceanography and Fisheries in Egipt supported this research.

Authorship contribution statement

R. Bendary: taxonomic identification of benthic invertebrates' species, performed the statistical analysis of the data, writing – the original draft, writing – the review & editing.

N. Imam: conceptualisation, validation, data analysis of radionuclides, writing – the original draft, writing – the review & editing.

Ethical Approval

Not applicable.

Code availability

Non-applicable.

Consent to participate

All authors voluntarily agree to participate in this research study.

Consent to publish

All authors voluntarily approved the publication of this research study.

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SUPPLEMENTARY MATERIALS

ST1 water Analysis

The water samples were kept in polyethylene bottles in an ice box and analyzed in a laboratory following the standard methods of the American Public Health Association (APHA 2005). The water samples' temperature and pH were measured in situ using a multiparameter (Hanna HI9829, Woonsocket, RI, USA). The transparency was measured using a white/black Secchi disk (30 cm in diameter). Total Dissolved Solids (TDS) were measured by filtering a known volume of a well-mixed sample volume through a glass microfiber filter (GF/C); the filtrate is evaporated to dryness in a weighed dish to constant weight at 180°C. The increase in weight represents the TDS. The modified Winkler method was used to measure DO.

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Table S1

Long-term changes of a physicochemical parameters in the water of Manzala Lake

Date	Temp.	Salinity ‰ (TDS)	pH	DO mg l^{-1}	References
1967		17.24			Youssef 1973
1985		5.37			El-Araby 1990
1986			7.6 - 8.8		Khedr 1989
1985-1986	12 - 30.1	0.4 - 36	7.34 - 10	2.4 - 15.0	Khalil 1990b
1993	20.7 ± 8.3		8.2 ± 0.6	6.85 ± 6.8	Badawy et al. 1995
1994					Zyadah (1995)
1997		2.13 - 39.13	7.6 - 8.8	0 - 9.8	Dewidar & Khedr (2001)
1999	17.6 - 30.5		6.69 - 8.8	0.0 - 5.9	Abdel-satar 2001
2000-2001			6.84 - 8.86	1.0 - 10.5	El-Enani 2004
2000-2001				0.51 - 14.30	Yacoub et al. 2005
2001	12.35 - 29.14	2.53	7.7 - 7.8	6.27 - 10.78	Shakwer 2005
2004		11 - 22.5	7.45 - 8.9	0 - 10.2	Ali 2008
2012	12.2 - 33	0.55 - 36	7.2 - 8.8	2.6 - 14.3	EL-Saharty 2014
2011	12.7 - 30.6		7 - 9.4	0 - 14.56	Elshemy 2016
2015	14 - 27.5	1.1 - 17.3	7.7 - 8.88	1.6 - 11.8	Elmorsi et al. 2017
2017-2018	14.3 - 35.5		7.68 - 9	0.7 - 12.4	Behary et al. 2019
2020	15.6 - 23.45	1.39 - 21.9	7.62 - 8.93	Nd - 14.7	Present study

Table S2

Community of benthic invertebrates (ind. m^{-2}) at the different stations in Manzala Lake

Class	Family	Species	n (Ind. m^{-2})										Average
			M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	
Mollusca													
Bivalvia	Cyrenidae	*Corbicula fluminalis*	38	25	0	25	0	0	0	38	125	0	25
	Cardiidae	*Cerastoderma glaucum*	63	0	250	50	0	0	63	0	0	0	43
	Tellinidae	*Macoma cumana*	0	0	63	25	0	0	0	0	0	0	9
Gastropoda	Thiaridae	*Melanoides tuberculata*	275	63	313	775	275	25	125	250	163	25	229
	Hydrobiidae	*Hydrobia ventrosa*	250	250	625	250	0	0	25	63	0	25	149
	Planorbidae	*Bulinus truncatus*	0	0	0	0	63	0	0	1313	0	0	138
		Gyraulus ehrenbergi	0	0	0	0	625	0	250	7000	0	125	800
		Helisoma duryi	0	0	0	0	0	0	0	0	0	13	1
		Biomphalaria alexandrina	0	0	0	0	375	0	250	0	0	0	63
	Paludomidae	*Cleopatra bulimoides*	0	0	0	0	25	0	0	0	563	0	59
	Ampullariidae	*Pila ovata*	0	0	0	0	0	0	125	0	0	0	13
	Bellamyinae	*Bellamya unicolor*	0	0	0	0	0	0	63	138	1875	25	210
	Lymnaeidae	*Lymnaea natalensis*	0	0	0	0	0	0	25	188	0	0	21
	Physidae	*Physa acuta*	0	0	0	0	0	0	0	125	0	0	13
	Neritidae	*Theodoxus niloticus*	0	0	0	0	0	0	0	0	25	0	3
	Potamididae	*Pirenella conica*	0	0	250	125	63	0	0	0	0	0	44
	Ampullariidae	*Lanistes carinatus*	0	0	0	0	500	0	0	0	0	0	50
		subtotal	625	338	1500	1250	1925	25	926	9113	2750	213	1866
Annelida													
Polychaeta	Nereididae	*Nereis diversicolor*	250	0	1750	0	0	0	0	0	0	0	200
	Serpulidae	*Ficopomatus enigmaticus*	250	0	0	0	0	0	0	0	0	0	25
	Spionidae	*Polydora ligni*	0	0	250	0	0	0	0	0	0	0	25
Clitellata	Salifidae	*Barbronia assiuti*	0	0	0	0	0	0	188	0	0	0	19
	Naididae	*Chaetogaster lamnaei*	0	0	88	0	0	0	0	0	0	0	9
		Branchiura sowerbyi	0	250	0	0	0	0	250	0	50	0	55
		Limnodrilus udekedmianus	125	0	125	0	0	0	0	0	0	500	75
		subtotal	625	250	2213	0	0	0	438	0	50	500	408
Arthropoda													
Ostracoda	Cyprididae	*Ostracodes* sp.	1875	1250	625	1875	625	250	1250	2188	313	125	1038
Thecostraca	Balanidae	*Amphibalanus amphitrite*	0	0	2250	0	0	0	125	0	0	0	238
Malacostraca	Corophiidae	*Corophium volutator*	0	0	6250	0	0	0	0	0	0	0	625
	Sphaeromatidae	*Sphaeroma* sp.	0	0	250	0	0	0	0	0	0	0	25
	Palaemonidae	*Palaemon elegans*	0	750	0	63	25	0	0	0	0	0	84
Insecta	Chironomidae	*Chironomus* sp.	188	0	0	75	0	0	188	0	0	25	48
		subtotal	2063	2000	9375	2013	650	250	1563	2188	313	150	2056
		Total	3313	2588	13088	3263	2575	275	2926	11300	3113	863	4330

Table S3

The concentration factors (CF) of radionuclides for total benthic invertebrates (L kg^{-1})

Sites	Ra-226 (U-238 series)		Th-232 series		K-40		Cs-137	
	winter	summer	winter	summer	winter	summer	winter	summer
M1	1.49×10^2	1.76×10^2	0.53×10^2	0.7×10^2	0.4×10^3	0.41×10^3	0.25×10^2	0.26×10^2
M2	1.36×10^2	1.61×10^2	0.7×10^2	0.9×10^2	0.54×10^3	0.54×10^3	0.27×10^2	0.24×10^2
M3	0.73×10^2	0.68×10^2	0.61×10^2	0.81×10^2	0.28×10^3	0.3×10^3	0.21×10^2	0.21×10^2
M4	1.13×10^2	0.9×10^2	0.69×10^2	1.07×10^2	0.8×10^3	0.75×10^3	0.21×10^2	0.23×10^2
M5	1.93×10^2	1.97×10^2	1.03×10^2	1.54×10^2	1.40×10^3	1.94×10^3	0.22×10^2	0.17×10^2
M6	0.7×10^2	0.83×10^2	1.26×10^2	1.67×10^2	0.25×10^3	0.25×10^3	0.31×10^2	0.2×10^2
M7	0.83×10^2	0.98×10^2	0.5×10^2	0.66×10^2	0.44×10^3	0.4×10^3	0.25×10^2	0.21×10^2
M8	3.4×10^2	5.17×10^2	0.87×10^2	1.51×10^2	0.58×10^3	0.74×10^3	0.17×10^2	0.17×10^2
M9	1.51×10^2	1.28×10^2	1.08×10^2	1.47×10^2	0.3×10^3	0.47×10^3	0.19×10^2	0.22×10^2
M10	1.49×10^2	1.76×10^2	1.29×10^2	1.72×10^2	0.38×10^3	0.38×10^3	0.24×10^2	0.22×10^2
Mean	1.5×10^2	1.7×10	0.86×10^2	1.2×10^2	0.54×10^3	0.62×10^3	0.23×10^2	0.21×10^2