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Critical remarks on radioactivity analysis in drinking waters: high doses and increased lifetime risks from Aqaba tap water, Jordan

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ABSTRACT

Radiochemical analysis was carried out on drinking water sources in the south region of Jordan. There is no information reported so far about radioactivity concentrations in drinking water. Therefore, gross alpha and beta activity concentrations were determined for tap water (TW), home filtered tap water, commercial water, and bottled water to evaluate age-dependent annual effective dose and lifetime risk. The activity concentrations range of gross alpha and beta in TW were 0.301–1.188, and 0.604–1.626 Bq L^{-1}, respectively. The results showed that, in general, activity concentrations in TW samples exceeded both World Health Organization and Jordanian guidelines of 0.5 and 1.0 Bq L^{-1} for gross alpha and beta, respectively. On the other hand, activity concentrations for other water sources were below the maximum allowable limits. The cancer lifetime risk from both ^{226}Ra and ^{228}Ra due to ingestion of TW exceed what some consider on acceptable risk of 10^{-4} or less. Therefore, all sources of water are safe for drinking and domestic purposes, except TW, which pose a hazard to public. Reverse osmosis filters are sufficient in removing radionuclides from TW, therefore, it is highly recommended for people to use them at their homes.

Keywords: Drinking water; Gross alpha and beta activity concentrations; Reverse osmosis; Aqaba; Age-dependent effective dose; Lifetime risk

1. Introduction

Natural radioactivity present in drinking water has gained increased attention since medical and biological research has determined that radiation exposure due to the ingestion of radionuclides can be harmful to humans. Humans are naturally exposed to radiation from either external (cosmic and terrestrial radiation) or internal (inhalation and ingestion) sources; natural background exposure is estimated at 2.4 mSv y^{-1} [1]. The occurrence of natural radionuclides in drinking water poses a hazard to the public. Radionuclides in drinking water results in human internal exposure, caused by the decay of radionuclides taken into the body through ingestion, and indirectly through inhalation, and both routes of exposure are incorporated as part of the human food chain [2]. Because of relatively high radiotoxicity of some naturally occurring radionuclides, the radiological water quality of drinking water should be monitored [3].

The lack of water resources is considered as one of the major environmental issues for the government of Jordan [4,5]. In fact, the Disi aquifer (ground water) has been the source of tap water in Aqaba for many years. The Disi aquifer is a large fossil water system located in the southern part of Jordan, which is one of major drinking water resources in Jordan [5]. The water has been pumped from this fossil aquifer to the capital city Amman, as well as to other governorates since July 2013 [4]. A mixing scenario was applied between Disi and non-Disi water to minimize the dose received by consumers to the recommended Jordanian standards [4]. Aqaba city, located at the southern part of Jordan, receives

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water directly from Disi aquifer. Most of Aqaba citizens drink tap water because they believe that Disi water is highly suitable for drinking and domestic purposes. In fact, these nonrenewable groundwater reservoirs are not expected to be free from radioactive elements due to natural decay series of uranium, thorium and actinium and other isotopes such as ^{40}K. The most important naturally occurring radionuclides that are present in water are the two radium isotopes ^{226}Ra and ^{228}Ra, which result from the decay of ^{238}U and ^{232}Th series, respectively. The chemical behavior of radium is similar to that of calcium in that radium is deposited in the human body, mainly in the bones [6,7].

Since water contains alpha emitters (^{238}U, ^{234}U, ^{230}Th, ^{226}Ra, ^{210}Po, ^{232}Th, and ^{228}Th) and beta emitters (^{40}K, ^{228}Ra and ^{210}Pb), gross alpha and gross beta could be determined in drinking water as a screening technique [8–10]. These isotopes may be responsible for a fraction of the internal exposure by ingestion of water, but they can also enter the food chain through irrigation waters [9,11]. Determination of gross alpha and beta activity concentrations in drinking water does not give insight into individual radionuclide concentrations, but it is important to determine dose estimations in the study of cumulative radiation effects on human health [3]. For practical purposes, the recommended guideline activity concentrations by the World Health Organization (WHO) for gross alpha and gross beta in drinking water are 0.5 and 1.0 Bq L^{-1}, respectively [12]. These guidelines are also recommended by the Jordanian standards and technical regulations [13]. If the screening levels of either gross alpha or gross beta activity concentrations are exceeded, then specific radionuclides should be identified and their individual activity concentrations must be measured [12]. When a source of drinking water contains unacceptably high concentrations of radionuclides, control options should be used such as the use of an alternative supply, controlled blending with another source or additional water treatment [12]. The choice of a suitable water treatment plant depends on the contaminant's chemical and physical characteristics. Moreover, other considerations should be taken into account such as the cost of treatment system, and service life. In fact, membrane processes such as reverse osmosis (RO) are efficiently removing many inorganic contaminants, including many toxic metals and radionuclides, such as radium and uranium [6, 12,14]. Montaña et al., compared many methods for removing radiological parameters from water and found that the removal rate of RO membranes exceeded 90% for gross alpha and beta, and total uranium activities [14].

There have been many studies worldwide which have determined radioactivity in drinking water, but in Jordan, few studies evaluated radioactivity in the drinking water for the region. Vengosh et al., determined the activity concentrations of radium isotopes for the first time in ground water from the Rum Group of the Disi aquifer in southern Jordan. They found that the activities of both ^{226}Ra and ^{228}Ra were 2000% higher than recommended limits for drinking water [15]. Al-Amir et al. measured gross alpha and beta activity concentrations, radium and uranium isotopes for tap water samples from the capital Amman and Aqaba. They found that the concentrations of radionuclides in Aqaba were much higher than that in Amman [16]. Subsequently, there have been no further published assessments regarding radioactivity concentrations in any other sources of drinking water in Aqaba. Therefore, it is important to determine gross alpha and beta activity concentrations to assess the radiological risk that is caused by drinking tap water. In the present study, four different categories of drinking water were evaluated: tap water selected from different houses, water treated by either RO membranes or by ion exchange (IE) softener, commercial water used for coolers, and finally bottled waters from the most common types found in the local markets. The aims of this study were:

1. To investigate radioactivity concentrations in all sources of drinking water and then to use household treatment methods for unsafe drinking water.
2. To evaluate the effectiveness of RO and IE for the removal of radioactivity in water.
3. To estimate the annual effective dose and cancer lifetime risk for all water sources.
4. To determine the best and safest option for consumers to use for drinking and domestic uses.

2. Materials and methods

2.1. Study area

Aqaba city, which is the only seaport in Jordan, attracts attention from Jordanians and foreign tourists throughout the year. It is located at the north eastern tip of the Gulf of Aqaba, which is an extension of the Red Sea in the southernmost part of Jordan. The Governorate is considered as a strategic region, which has boundaries with Saudi Arabia, Egypt, and Eilat [17]. Recently, its population has been estimated at about 188,160 inhabitants in an area of ≈6,904.7 km^2. Aqaba has become a special economic zone to enhance the region and create a suitable environment for development and investment since 2001. It includes important industrial establishments and commercial free zones [17]. The phosphate industry is considered as one of the main anthropogenic activities in the coastal area and Jordan is known as the fifth largest producer and the third largest exporter of phosphate rocks [18].

2.2. Sample collection and preparation

Twenty three tap water samples as well as four samples of filtered tap water were collected in triplicate from different locations in Aqaba as shown in Fig. 1. Collecting tap water samples from all regions in the city was one goal for the sampling strategy. Fifteen samples were collected from five commercial retail sources for plastic water cooler dispenser bottles (commercial water) widely used water coolers in homes for drinking. Finally, nine brands of most commonly used bottled water consumed by people in Aqaba were purchased from local commercial retail sources. Three bottles of each water brand were collected for analysis.

Physico-chemical parameters (total dissolved solids [TDS], pH, and conductivity) of water samples can provide important firsthand information about drinking water quality. The TDS, pH, and conductivity were all determined directly at the time of collection using standard procedures. A known volume of each water sample (50 ml) was evaporated until dryness and then the residue with the glass were

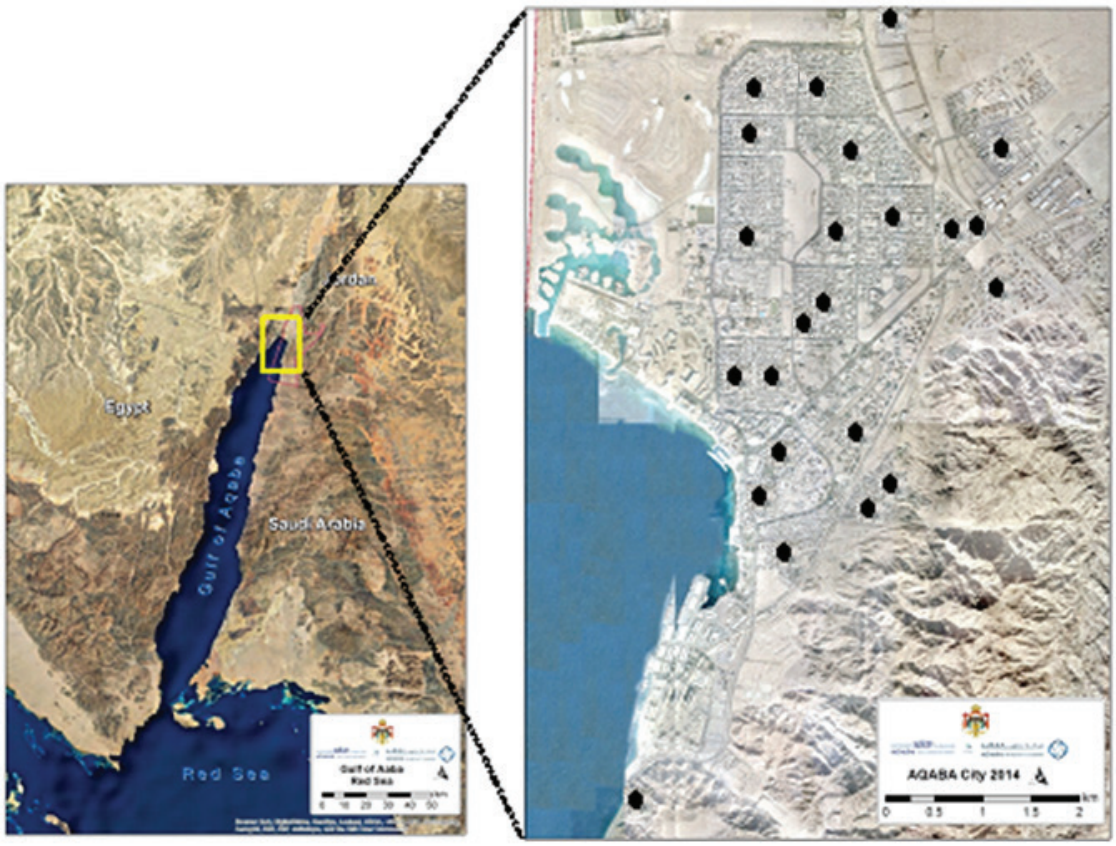

Fig. 1. Map of Aqaba and selected sites of all drinking water samples.

weighted after it was weighted alone. The TDS is determined from the difference between both weights. The pH meter and conductivity meter were used easily to determine pH and conductivity of water samples, respectively. The bottles were first rinsed three times with doubly distilled water before sampling. After that, all water samples were counted for gross alpha and beta activity concentrations after preparation.

All samples were prepared for measurement according to Krieger, and ASTM D7283–17 method [19,20]. 100 ml of each water sample was reduced to dryness under infrared (IR) lamp, the residue was transferred to a glass scintillation vial, washed with 5 ml of 1 M HNO_3, transferred to a liquid scintillation counter (LSC) vial, and evaporated under IR lamp to dryness. The residue was dissolved in 1ml of 1M HNO_3 and then 15 ml of Ultima Gold™ AB scintillation cocktail were added to the vial. After mixing and set in dark for approximately an hour, it was cleaned with ethanol before counting; each water sample was counted for 500 min. Gross alpha and beta activity concentrations were performed using LSC from Perkin Elmer Tri-Crab 3170TR/LS analyzer equipped with a pulse shape analyzer. The system was calibrated using certified standard solutions of Am-214 and Sr-90.

2.3. Equations and calculations

2.3.1. Gross alpha and gross beta activity concentrations

Alpha or beta radioactivity concentration (A) in Bq L^{-1} is calculated by the following equation [21]:

$$A = \frac{A_{\alpha,\beta}}{\varepsilon_{\alpha,\beta} \times V \times 60} \quad (1)$$

where $A_{\alpha,\beta}$ is the net alpha or beta count rate (CPM), $\varepsilon_{\alpha,\beta}$ is gross alpha or beta efficiency, and V is the volume of water sample (L).

2.3.2. Gross alpha and gross beta detection efficiency

Gross alpha/beta detection efficiency ($\varepsilon_{\alpha,\beta}$) is calculated using the corresponding standard solution of pure alpha and beta emitters by the following equation [21]:

$$\varepsilon = \frac{\text{CPM}}{\text{DPM}} \quad (2)$$

where CPM is the net alpha/beta count rate per minute, and DPM is the disintegration per minute. In this study, three samples were prepared for efficiency determination using Am-241 as an alpha emitter and Sr-90 as a beta emitter. In this work, alpha and beta particles detection efficiencies were calculated as ≈100%, and ≈96.4%, respectively.

2.3.3. Minimum detectable activity

The minimum detectable activity (MDA) in Bq L^{-1} is calculated using equation below [11,22]:

$$\mathrm{MDA} = \left(\frac{2.71 + 4.65\sqrt{BT}}{60\varepsilon TV} \right) \quad (3)$$

where B is the background count rate (counts per minute), T is the measurement time (min), V is the volume of a sample (L), and ε is the efficiency [11]. In this study, MDA for gross alpha and beta activity concentrations (MDA_{α} and MDA_{β}) were calculated as 0.041 and 0.118 Bq L^{-1}, respectively.

2.3.4. Measurement of uncertainties

The contribution of uncertainty sources related to the calculation of activity concentration is evaluated from the relative uncertainties as follows:

$$\sigma_A = A\sqrt{\left(\frac{\sigma_{\mathrm{nc}}}{\mathrm{nc}}\right)^2 + \left(\frac{\sigma_V}{V}\right)^2 + \left(\frac{\sigma_\varepsilon}{\varepsilon}\right)^2} \quad (4)$$

where A is the activity concentration (Bq L^{-1}), σ_{nc} is the uncertainty in the net count rate, σ_V is the uncertainty in the sample volume, and σ_ε is the uncertainty in the counting efficiency. The relative uncertainty in the counting efficiency is calculated as follows:

$$\sigma_\varepsilon = \varepsilon\sqrt{\left(\frac{\sigma_{\mathrm{nc}}}{\mathrm{nc}}\right)^2 + \left(\frac{\sigma_w}{w}\right)^2 + \left(\frac{\sigma_{A_s}}{A_s}\right)^2 + \left(\frac{\sigma_t}{T_{1/2}}\right)} \quad (5)$$

where σ_w is the uncertainty in the weight of the spiked activity, σ_{A_s} is the uncertainty in the activity of the standard, and σ_t is the uncertainty in the half live of the standard radionuclide.

The uncertainty of the net count rate is calculated by:

$$\sigma_{\mathrm{nc}} = \sqrt{(\sigma_C)^2 + (\sigma_B)^2} \quad (6)$$

where σ_C is the uncertainty in the count rate, and σ_B is the uncertainty in the background count rate.

2.3.5. Effective dose

The associated age-dependent effective dose, E_d (Sv y^{-1}), due to water consumption is estimated using the following equation [16,23]:

$$E_d = D_{\mathrm{cf}} W_{\mathrm{ac}} C \quad (7)$$

where D_{cf} is the ingestion dose conversion factor for a specific radionuclide (Sv Bq^{-1}) and values were taken from IAEA safety standard series, 2011 (Tables 5 and 9) [24,25], W_{ac} is the water annual consumption rates of water for people of different age groups: ≤1, 1–2, 2–7, 7–12, 12–17 and >17 y, which are 250, 300, 350, 440, 550 and 730 L y^{-1}, respectively [23], and C is the activity concentration of a specific radionuclide (Bq L^{-1}). The recommended reference dose levels (RDL) by WHO (2011), and JISM (2015) for ingestion of drinking water are 0.1, and 0.5 mSv y^{-1}, respectively [12,13,26].

2.3.6. Lifetime risk assessment

The nominal probability coefficient for radiation induced stochastic health effects (fatal cancer, non-fatal cancer and severe hereditary effects for the whole population) recommended by ICRP (2008) and used for calculation in this study is 5.5×10^{-2}/Sv [12,27]. That coefficient could be multiplied by RDL, the annual exposure via drinking water, to calculate an estimated upper bound lifetime risk of stochastic health effects [12,26]. This is approximately equivalent to the 10^{-5} excess lifetime risk of cancer (i.e. one excess case of cancer per 100,000 people ingesting drinking-water at the water quality target daily over a 70-y period), which is the risk level used in WHO guidelines (2008 and 2011) as well as previous editions of the guidelines to determine guideline values for genotoxic carcinogens [12,26]. In fact, the acceptable risk could be approximated to be 10^{-4} or less, which was smaller than many other health risks.

2.3.7. Removal rate calculation

Removal rates (RE) for gross alpha and gross beta activity concentrations for different water treatment methods (RO and IE) are calculated by the following equation [14,28]:

$$\mathrm{RE}\% = \left(\frac{\mathrm{A}_o - \mathrm{A}_f}{\mathrm{A}_o}\right) \times 100\% \quad (8)$$

where A_o is the initial activity concentration in the raw water before passing through the filter (Bq L^{-1}), and A_f is the final activity concentration after passing through the filter (Bq L^{-1}).

The best removals for gross alpha and gross beta activity concentrations are by RO treatment. RO can remove 87–98% of radium from drinking water and similar elimination can be achieved for alpha, beta and photon emitters [14,29].

3. Results and discussion

3.1. Activity concentrations and physico-chemical parameters

3.1.1. Tap water

The mean values of activity concentrations of gross alpha and beta, TDS, pH, and conductivity in tap drinking water from different areas in Aqaba are summarized in Table 1. The gross alpha and gross beta activity concentrations in tap water ranged between 0.301–1.188, and 0.604–1.626 Bq L^{-1}, respectively. Gross beta activities were higher than the corresponding gross alpha activities (Table 1). All values of gross alpha activity concentrations in all investigated tap water samples were higher than the recommended limits by both WHO (2011) and Jordanian drinking water standards (2015) of 0.5 Bq L^{-1} except for T4, T16, T17, and T20 samples [12,13]. All values of gross beta activity concentrations in tap water samples exceeded the recommended limit of 1.0 Bq L^{-1} except for T4, T5, T9, T16, T17, and T20 samples [12,13]. A strong linear correlation (R = 0.87) was found between gross alpha

Table 1
Gross alpha and gross beta activity concentrations, TDS, pH, and conductivity in tap water from Aqaba city

Sample ID	Gross alpha (Bq L^{-1})	Gross beta (Bq L^{-1})	TDS (mg L^{-1})	pH	Conductivity (μS)
T1	1.188±0.276	1.612±0.094	204.0	7.54	383.0
T2	1.065±0.248	1.520±0.090	220.0	7.51	379.0
T3	0.732±0.171	0.994±0.066	93.0	7.56	372.0
T4	0.301±0.072	0.612±0.051	203.5	7.55	381.0
T5	0.653±0.152	0.864±0.060	252.5	7.73	369.0
T6	0.855±0.199	1.162±0.073	214.0	7.56	381.0
T7	0.805±0.188	1.535±0.090	161.5	7.28	365.0
T8	1.044±0.243	1.612±0.094	215.5	7.53	381.0
T9	0.671±0.157	0.899±0.062	204.5	7.50	360.0
T10	1.136±0.264	1.461±0.087	225.0	7.62	386.0
T11	0.971±0.226	1.363±0.082	247.0	7.64	374.0
T12	0.867±0.202	1.312±0.080	220.5	7.64	381.0
T13	0.714±0.166	1.626±0.095	231.5	7.64	383.0
T14	0.877±0.204	1.206±0.075	302.0	8.13	563.0
T15	0.623±0.146	1.075±0.069	250.0	7.50	374.0
T16	0.395±0.093	0.726±0.055	109.0	7.50	376.0
T17	0.425±0.100	0.702±0.054	174.0	7.52	383.0
T18	0.718±0.168	1.210±0.075	239.0	7.54	387.0
T19	0.760±0.177	1.054±0.068	185.0	7.54	379.0
T20	0.388±0.092	0.604±0.050	191.0	7.55	381.0
T21	0.638±0.149	0.919±0.062	232.0	7.62	378.0
T22	0.796±0.185	0.994±0.066	223.0	7.56	363.0
T23	0.594±0.139	0.919±0.063	225.0	7.64	380.0
Mean	0.748±0.175	1.130±0.072	209.7	7.58	385.2
Max.	1.188	1.626	302.0	8.13	563.0
Min.	0.301	0.604	93.0	7.28	360.0

and gross beta activity concentrations in drinking tap water (Fig. 2). This correlation indicates that similar radionuclides might be responsible for the contamination of the ground water are coming from natural radionuclides [30].

No wide variations were found in the pH values, which ranged from 7.28 to 8.13 with an average of 7.58. It is expectable to find low difference in the pH values. No correlations were found between pH and gross alpha activity concentration (R = 0.13) and pH with gross beta activity concentration (R = 0.01). These correlations indicate that there was no effect of pH on gross alpha and beta activities. TDS values ranged between 93 and 302 mg L^{-1}. Weak correlations were found between gross alpha activity concentration and TDS (R = 0.32) and gross beta activity concentration and TDS (R = 0.28), which indicates a weak effect of TDS on gross alpha and beta activities. In addition, the conductivity range of tap water samples was 360–563 μS.

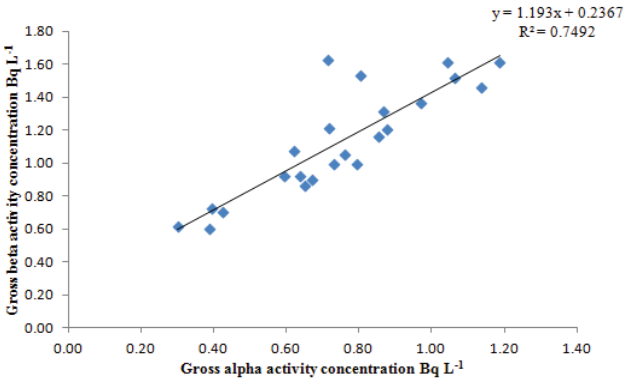

Fig. 2. Relation between gross alpha and gross beta activity concentrations for tap water samples.

3.1.2. Home filtered water

Because of high values of gross alpha and beta activity concentrations in tap water, treatment methods were required for treatment of drinking water. RO membranes and IE softener were used in selected homes from different locations in Aqaba. RO was used in three different homes, whereas, IE was used in only one site. Gross alpha and beta activities were decreased significantly. The ranges of gross alpha and beta activity concentrations were ranged from $<MDA_{\alpha}$ to 0.081 and $<MDA_{\beta}$ to 0.229 Bq L^{-1}, respectively (Table 2). To approximate the quantity of reduction or removal of radionuclides by using RO and IE, the removal rate was calculated for each sample. The removal rates were 93.6% and 95.3% (mean values) for gross alpha activity concentration by using RO and IE treatments, respectively. Whereas, the removal rates values of gross beta activity concentration using RO and

IE treatments were 87.8% and 90.2%, respectively. Although radionuclides were removed from tap water by using either RO or IE, the water recovery was low leaving the wastewater, fraction which contained the contaminants. This wastewater fraction has subsequently been used for irrigation when it should be sent to a wastewater treatment system. As a result, radionuclides may enter into food chain through that contaminated water [9,11]. Additionally, on-site wastewater treatment systems increase the contaminant loading on septic systems. Because of the RO system's inefficiency, it is typically used to treat water only for drinking and cooking. If large amounts of water are needed, a better treatment option may be ion exchange method.

Other water properties were determined for filtered tap water (TDS, pH, and conductivity) as shown in Table 2. The ranges of TDS, pH, and conductivity in treated water by RO were 6.0–39.0 mg L^{-1}, 7.97–8.14, and 19.3–34.3 μS, respectively. In addition, TDS, pH, and conductivity in treated water by IE were 143.0 mg L^{-1}, 7.8, and 183.7 μS, respectively. From these results, it was clear that both TDS and conductivity were significantly decreased after passing through RO filters. Whereas, TDS and conductivity of tap water post- IE filtration decreased by approximately 50% and 66%, respectively.

3.1.3. Commercial water

Large volume water cooler dispenser bottle water samples obtained from five commercial retail sources in Aqaba were analyzed to determine gross alpha and beta activity concentrations in commercial waters. Gross alpha and beta activity concentrations were $<MDA_{\alpha}$ – 0.200, $<MDA_{\beta}$ – 0.353 Bq L^{-1}, respectively. The TDS, pH, and conductivity value ranges were 14.0–200.0 mg L^{-1}, 7.68–7.96, and 56.5–319.0 μS, respectively (Table 3). All values of gross alpha and beta activity concentrations from commercial water were below the maximum allowable limits.

3.1.4. Bottled water

Nine brands of the most commonly available bottled water in Aqaba (UT, AQ, GH, NT, MF, RV, NJ, RS, and AR) were analyzed for gross alpha and beta activity concentrations. The range of gross alpha and beta activity concentrations were $<MDA_{\alpha}$ – 0.249, $<MDA_{\beta}$ – 0.303 Bq L^{-1}, respectively. TDS, pH, and conductivity were determined in all samples, and their ranges were 21.0–307.0 mg L^{-1}, 7.27–7.97, and 18–547.0 μS, respectively (Table 4). Gross alpha and beta activity concentrations were below both the national and international maximum allowable limits for all water samples.

3.1.5. Factors affect gross alpha and beta in tap water

There is some interest by the public in determining whether the boiling of water effects the levels of gross alpha and beta activity concentrations in tap water. Therefore, two tap water samples were selected randomly (T9 and T23) to evaluate this effect by comparing the activities before and after boiling. Gross alpha activity concentrations for these two selected samples were 0.671±0.157 and 0.594±0.139 Bq L^{-1} and gross beta activity concentrations were 0.899±0.062 and 0.919±0.063 Bq L^{-1}, respectively. After boiling, gross alpha activity concentrations increased to 0.990±0.230 and 1.000±0.233 Bq L^{-1}, and gross beta activity concentrations increased to 1.261±0.078 and 1.509±0.089 Bq L^{-1}, respectively. The reason for the increased activities may be due to the evaporation of contaminant-free water during heating or boiling, leaving behind concentrated contaminants and therefore increasing the exposure levels of consumption. Murad et al., reported that the effect of temperature on radionuclides at aquifers was difficult to determine [31]. Therefore, further analysis is required to study the effect of heat on radionuclides in tap water.

Table 2
Gross alpha and gross beta activity concentrations from water samples treated by (RO) membrane and ion exchange (IE) as well as TDS, pH, and conductivity

Treatment method	Sample ID	Gross alpha (Bq L^{-1})	Gross beta (Bq L^{-1})	TDS (mg L^{-1})	pH	Conductivity (μS)
RO	F2	$<MDA_{\alpha}$ [a]	$<MDA_{\beta}$ [b]	39.0	8.11	25.8
	F6	0.081±0.023	0.229±0.039	6.0	7.97	19.3
	F12	0.051±0.018	$<MDA_{\beta}$	11.5	8.14	34.3
IE	F14	$<MDA_{\alpha}$	$<MDA_{\beta}$	143.0	7.80	183.7

[a]Minimum detectable activity for gross alpha.
[b]Minimum detectable activity for gross beta.

Table 3
Gross alpha and gross beta activity concentrations from commercial water samples as well as TDS, pH, and conductivity

Sample ID	Gross alpha (Bq L^{-1})	Gross beta (Bq L^{-1})	TDS (mg L^{-1})	pH	Conductivity (μS)
C1	0.072±0.021	0.136±0.038	200.0	7.82	319.0
C2	0.093±0.025	0.162±0.038	85.0	7.86	168.5
C3	0.200±0.049	0.353±0.042	44.0	7.68	175.0
C4	$<MDA_{\alpha}$	$<MDA_{\beta}$	18.5	7.96	56.5
C5	0.148±0.037	0.215±0.039	14.0	7.73	178.7

Table 4
Gross alpha and gross beta activity concentrations for bottled drinking water samples as well as TDS, pH, and conductivity

Sample ID	Gross alpha (Bq L^{-1})	Gross beta (Bq L^{-1})	TDS (mg L^{-1})	pH	Conductivity (μS)
UT	MDA_{α}	MDA_{β}	21.0	7.94	18.3
AQ	MDA_{α}	MDA_{β}	99.5	7.60	211.0
GH	0.249±0.060	0.303±0.040	307.0	7.35	547.0
NT	MDA_{α}	0.497±0.046	156.0	7.27	241.0
MF	MDA_{α}	MDA_{β}	98.5	7.59	170.3
RV	MDA_{α}	MDA_{β}	28.5	7.97	43.5
NJ	0.140±0.035	0.264±0.040	125.5	7.51	175.0
RS	0.147±0.037	0.193±0.039	137.0	7.66	268.0
AR	MDA_{α}	MDA_{β}	168.5	7.70	271.0

It is important to investigate the levels of gross alpha and beta activity concentrations in water that is stored in tanks for long periods of time. Because of very hot weather during the summer months, many Aqaba citizens spend this time away from their homes. This absence might extend from a month up to three months in some cases which will make water at home tanks to become stagnant. In order to investigate the effect of storage time on gross alpha and beta activity concentrations, tap water samples were selected randomly, stored in similar conditions as stagnant water tanks, in plastic bottles for more than two months, and then re-analyzed for gross alpha and beta activity concentrations after storage. For this purpose, T4, T5, T12, T16, T17, T20, and T21 water samples were reanalyzed. Gross alpha and beta activity concentrations in these samples were comparable or higher than their first measurement as shown in Figs. 3(a) and (b). After storage, gross beta activity concentrations increased by more than double the activities before storage. While, gross alpha activities (after storage) increased slightly. This might be due to the random nature of radioactivity. However, it could be suggested that public consumption of stored water is not safe. Further analysis is recommended to study the effect of storage time on levels of radioactivity in tap water.

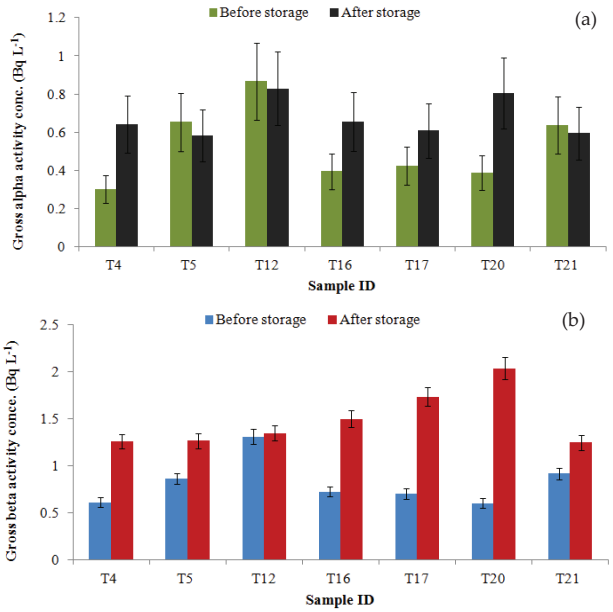

Fig. 3. (a) Gross alpha activity and (b) Gross beta activity concentration before/ after storage in (Bq L^{-1}) for selected tap water samples.

3.2. Annual effective dose estimations and lifetime risk assessment

In this work, the origin of gross alpha and beta activity concentrations were not determined. But it is known that gross alpha activity concentration in groundwater mainly comes from the decay of uranium and radium isotopes since thorium has low solubility in water and strong sorption properties [9,16]. Besides, the major beta emitting radionuclides are ^{210}Pb, ^{228}Ra, and ^{40}K [32,33]. In radiological studies, ^{226}Ra and ^{228}Ra are considered as the largest contributors of gross alpha and beta activities, respectively because of their carcinogenic effect, they can lead to human bone cancer [16,30]. Other radium isotopes (^{223}Ra and ^{224}Ra) have relatively short half-lives, on the order of days; therefore, not of a concern in this work. Many researchers have calculated effective doses by assuming that gross alpha activity comes only from ^{226}Ra, whereas, gross beta activity comes only from ^{228}Ra without subtracting the ^{40}K contribution from the gross beta activity [16,34]. This assumption represents the worst-case scenario that the doses calculated here represent the maximum ingestion dose due to ingestion of tap water from Aqaba. Because of different consumption rates of water for people at different ages, the annual effective dose, E_d (Sv y^{-1}), due to the ingestion of tap water was calculated for six age classes. The mean values of annual effective dose of ^{226}Ra and ^{228}Ra for ≤1, 1–2, 2–7, 7–12, 12–17 and >17 y were 9.352, 2.148, 1.506, 2.202, 3.911, and 0.722 mSv y^{-1}, respectively (Table 5). These values of age dependent doses from tap water in Aqaba were much higher than the international recommended reference dose level (RDL) of (0.1mSv y^{-1}) [12,26]. Also, they exceeded the Jordanian standard of 0.5mSv y^{-1}, which is 5 times higher than WHO limit [13]. Based on these results, it is observed that the annual effective dose due to ^{228}Ra was higher than the dose due to ^{226}Ra for all age groups. The annual effective dose of ^{228}Ra for infant (≤1 y) and adolescent (12–17 y) groups were much higher than other age groups. These stages of human growth are considered as critical stages due to mineralization and deposit active calcium of bones during these life stages. This result indicates that those age groups are more likely subjected to risk due to their intensive bone growth in these stages [7,23]. Also, high values of radium effective doses for infants and adolescents could be connected with hormone production in the

body such as testosterone [7]. This hormone affects bone calcification and is produced in higher concentrations during these life stages. Higher production of these hormones could explain a higher absorption of radium. Adults and especially elderly people with reduced metabolic functions are much less susceptible to the presence of radium [7].

On the contrary, the annual effective dose by the ingestion of filtered water (FW), commercial water (CW), and bottled water (BW) were estimated (worst case scenario) for all age groups (Table 6). As found for tap water, infants and adolescents were the most critical groups because they received the highest doses via drinking water from different

Table 5
Mean value of annual effective dose (mSv y^{-1}) due to ingestion of ^{226}Ra and ^{228}Ra in drinking tap water from Aqaba with dose conversion factors (Sv Bq^{-1}) for different age classes

		>17 y	12–17 y	7–12 y	2–7 y	1–2 y	≤1 y
^{226}Ra	D_{cf}	2.8×10^{-7}	1.5×10^{-6}	8.0×10^{-7}	6.2×10^{-7}	9.6×10^{-7}	4.7×10^{-6}
	E_d	0.153	0.618	0.264	0.162	0.216	0.880
^{228}Ra	D_{cf}	6.9×10^{-7}	5.3×10^{-6}	3.9×10^{-6}	3.4×10^{-6}	5.7×10^{-6}	3.0×10^{-5}
	E_d	0.569	3.293	1.938	1.344	1.932	8.472
Total Ra	E_d	0.722	3.911	2.202	1.506	2.148	9.352

Table 6
Mean value of annual effective dose (mSv y^{-1}) due to ingestion of ^{226}Ra and ^{228}Ra in filtered, commercial, and bottled waters from Aqaba for different age classes

Water source			>17 y	12–17 y	7–12 y	2–7 y	1–2 y	≤1 y
FW		^{226}Ra	0.010	0.042	0.018	0.011	0.015	0.059
		^{228}Ra	0.054	0.314	0.185	0.128	0.184	0.808
		Total Ra	0.064	0.356	0.203	0.139	0.199	0.867
CW		^{226}Ra	0.023	0.092	0.039	0.024	0.032	0.130
		^{228}Ra	0.099	0.573	0.338	0.234	0.336	1.475
		Total Ra	0.122	0.665	0.337	0.258	0.368	1.605
BW	UT	^{226}Ra	0.008	0.034	0.014	0.009	0.012	0.048
		^{228}Ra	0.059	0.344	0.203	0.140	0.202	0.885
		Total Ra	0.067	0.378	0.217	0.149	0.214	0.933
	AQ	^{226}Ra	0.008	0.034	0.014	0.009	0.012	0.048
		^{228}Ra	0.059	0.344	0.203	0.140	0.202	0.885
		Total Ra	0.067	0.378	0.217	0.149	0.214	0.933
	GH	^{226}Ra	0.051	0.205	0.088	0.054	0.072	0.293
		^{228}Ra	0.153	0.883	0.520	0.361	0.518	2.273
		Total Ra	0.204	1.088	0.608	0.415	0.590	2.566
	MF	^{226}Ra	0.008	0.034	0.014	0.009	0.012	0.048
		^{228}Ra	0.059	0.344	0.203	0.140	0.202	0.885
		Total Ra	0.067	0.378	0.217	0.149	0.214	0.933
	RV	^{226}Ra	0.008	0.034	0.014	0.009	0.012	0.048
		^{228}Ra	0.059	0.344	0.203	0.140	0.202	0.885
		Total Ra	0.067	0.378	0.217	0.149	0.214	0.933
	NJ	^{226}Ra	0.029	0.115	0.049	0.030	0.040	0.164
		^{228}Ra	0.133	0.771	0.454	0.315	0.452	1.983
		Total Ra	0.162	0.886	0.503	0.345	0.492	2.147
	RS	^{226}Ra	0.030	0.121	0.052	0.032	0.042	0.172
		^{228}Ra	0.097	0.563	0.331	0.230	0.330	1.448
		Total Ra	0.127	0.684	0.383	0.262	0.372	1.620
	AR	^{226}Ra	0.008	0.034	0.014	0.009	0.012	0.048
		^{228}Ra	0.059	0.344	0.203	0.140	0.202	0.885
		Total Ra	0.067	0.378	0.217	0.149	0.214	0.933
	NT	^{226}Ra	0.008	0.034	0.014	0.009	0.012	0.048
		^{228}Ra	0.250	1.449	0.853	0.591	0.850	3.728
		Total Ra	0.258	1.483	0.867	0.600	0.862	3.776

sources. From the results, it is clear that filtration is the best choice for a family to use at home to reduce radiation doses. Furthermore, many brands of bottled waters are highly recommended as a source for drinking water since the radiation doses from radium for adults were below both WHO and Jordanian guidelines (Table 6). Whereas, the radiation doses for adults from drinking the water of GH, NJ, RS, and NT brands exceeded the acceptable limits recommended by WHO, but they were still below the Jordanian acceptable limits.

In this study, the annual effective doses due to intake of other alpha and beta emitters (^{238}U, ^{234}U, ^{230}Th, ^{210}Po, ^{232}Th, ^{228}Th, and ^{210}Pb) through drinking water for all sources of water at Aqaba city were estimated to assess the health risk for all age classes (Tables 7 and 8). The results from this study showed that the annual effective doses for adults via ingestion of home filtered tap water (FW) and commercial water (CW) were below the WHO recommended reference level of 0.1 mSv y^{-1}, while the annual effective dose from ^{210}Po and ^{210}Pb due to ingestion of tap water and some brands of bottled waters (GH, NJ, RS, and NT) were higher than WHO limit (0.1 mSv y^{-1}) for most age classes (Tables 7 and 8). Also, the estimation of radiation dose due to intake of uranium for different age groups is of great importance since uranium is a well-known nephrotoxic heavy metal that causes chemical damage to the kidneys [35]. The uranium radiation doses from tap water (TW), FW, CW, and all brands of bottled water (BW) were much lower than both WHO and Jordanian guidelines.

It was reported by WHO that the lifetime risk of cancer in humans could be increased due to the long-term ingestion of contaminated drinking water by radionuclides [12]. Therefore, the lifetime risk of cancer from ingestion of all alpha and beta emitters were estimated for all sources of drinking water in Aqaba (Table 9).

The lifetime risk of cancer due to the ingestion of TW was estimated. The risk due to the estimated doses from both ^{226}Ra and ^{228}Ra for were 2.9×10^{-4}, and 1.1×10^{-3}, respectively (Table 9). This risk from ^{226}Ra slightly exceeded the acceptable risk of 10^{-4} or less, but the risk from ^{228}Ra was more significant than 10^{-4}. In fact, these values were overestimated due to the contribution of ^{40}K to the gross beta activity. The mean value of lifetime risk due to intake of ^{230}Th, ^{210}Po, ^{232}Th, and ^{210}Pb through drinking TW exceeded what some consider on acceptable risk of 10^{-4} or less. In addition, the mean value of lifetime risk due to intake of ^{210}Po and ^{210}Pb through drinking CW slightly exceeded the acceptable limit of 10^{-4} or less. Conversely, the results showed that the lifetime risk from consuming FW were below or equal to the acceptable limit. Unexpectedly, it was found that the lifetime risk from drinking some brands of BW (GH, NJ, RS, and NT) due to intake of ^{210}Po, ^{228}Ra, and ^{210}Pb slightly exceeded the acceptable limit of 10^{-4} or less. But, other investigated BW brands seem to be safe since the mean values of lifetime risks were below or equal to the acceptable limit. These results indicate that consuming tap water is not recommended for all age groups. For a more accurate risk assessment for tap water, more measurements of natural radioactivity in drinking water are still needed. Therefore, it is highly recommended to identify the radionuclides in water and then choose a suitable method or methods for removing contaminants in order to prevent undesirable deposition of hazardous elements into the bone during development and to reduce the risk of occurrence of bone sarcomas later in life.

Table 7
The average annual effective doses of alpha and beta emitters in tap, filtered, and commercial water samples for different age classes (mSv y^{-1})

Age class (y)	Water source	^{238}U	^{234}U	^{230}Th	^{210}Po	^{232}Th	^{228}Th	^{210}Pb
>17	TW	0.025	0.027	0.115	0.656	0.126	0.039	0.569
	FW	0.002	0.002	0.008	0.044	0.009	0.003	0.054
	CW	0.004	0.004	0.017	0.097	0.019	0.006	0.099
12–17	TW	0.028	0.031	0.091	0.659	0.103	0.039	1.180
	FW	0.002	0.002	0.006	0.044	0.007	0.003	0.113
	CW	0.004	0.005	0.013	0.098	0.015	0.006	0.206
7–12	TW	0.022	0.024	0.079	0.856	0.096	0.046	0.944
	FW	0.002	0.002	0.005	0.058	0.006	0.003	0.090
	CW	0.003	0.004	0.012	0.127	0.014	0.007	0.164
2–7	TW	0.021	0.023	0.081	1.153	0.092	0.058	0.870
	FW	0.001	0.002	0.006	0.078	0.006	0.004	0.083
	CW	0.003	0.003	0.012	0.171	0.014	0.009	0.151
1–2	TW	0.027	0.029	0.092	1.976	0.101	0.083	1.220
	FW	0.002	0.002	0.006	0.133	0.007	0.006	0.116
	CW	0.004	0.004	0.014	0.293	0.015	0.012	0.212
≤1	TW	0.064	0.069	0.767	4.865	0.861	0.692	2.372
	FW	0.004	0.005	0.052	0.327	0.058	0.047	0.226
	CW	0.009	0.010	0.114	0.722	0.128	0.103	0.413

Table 8
The annual effective doses of alpha and beta emitters in different bottled water samples for different age classes (mSv y^{-1})

Age class (y)	Radionuclide	UT	AQ	GH	MF	RV	NJ	RS	AR	NT
>17	^{238}U	0.001	0.001	0.008	0.001	0.001	0.005	0.005	0.001	0.001
12–17		0.002	0.002	0.009	0.002	0.002	0.005	0.005	0.002	0.002
7–12		0.001	0.001	0.008	0.001	0.001	0.004	0.004	0.001	0.001
2–7		0.001	0.001	0.007	0.001	0.001	0.004	0.004	0.001	0.001
1–2		0.002	0.002	0.009	0.002	0.002	0.005	0.005	0.002	0.002
≤1		0.004	0.004	0.021	0.004	0.004	0.012	0.013	0.004	0.004
>17	^{234}U	0.002	0.002	0.009	0.002	0.002	0.005	0.005	0.002	0.002
12–17		0.002	0.002	0.010	0.002	0.002	0.006	0.006	0.002	0.002
7–12		0.001	0.001	0.008	0.001	0.001	0.005	0.005	0.001	0.001
2–7		0.001	0.001	0.008	0.001	0.001	0.004	0.005	0.001	0.001
1–2		0.002	0.002	0.010	0.002	0.002	0.006	0.006	0.002	0.002
≤1		0.004	0.004	0.023	0.004	0.004	0.013	0.014	0.004	0.004
>17	^{230}Th	0.006	0.006	0.038	0.006	0.006	0.021	0.023	0.006	0.006
12–17		0.005	0.005	0.030	0.005	0.005	0.017	0.018	0.005	0.005
7–12		0.004	0.004	0.026	0.004	0.004	0.015	0.016	0.004	0.004
2–7		0.004	0.004	0.027	0.004	0.004	0.015	0.016	0.004	0.004
1–2		0.005	0.005	0.031	0.005	0.005	0.017	0.018	0.005	0.005
≤1		0.042	0.042	0.255	0.042	0.042	0.143	0.150	0.042	0.042
>17	^{210}Po	0.036	0.036	0.218	0.036	0.036	0.123	0.129	0.036	0.036
12–17		0.036	0.036	0.219	0.036	0.036	0.123	0.129	0.036	0.036
7–12		0.047	0.047	0.285	0.047	0.047	0.160	0.168	0.047	0.047
2–7		0.063	0.063	0.384	0.063	0.063	0.215	0.226	0.063	0.063
1–2		0.108	0.108	0.657	0.108	0.108	0.369	0.387	0.108	0.108
≤1		0.267	0.267	1.619	0.267	0.267	0.909	0.954	0.267	0.267
>17	^{232}Th	0.007	0.007	0.042	0.007	0.007	0.024	0.025	0.007	0.007
12–17		0.006	0.006	0.034	0.006	0.006	0.019	0.020	0.006	0.006
7–12		0.005	0.005	0.032	0.005	0.005	0.018	0.019	0.005	0.005
2–7		0.005	0.005	0.031	0.005	0.005	0.017	0.018	0.005	0.005
1–2		0.006	0.006	0.034	0.006	0.006	0.019	0.020	0.006	0.006
≤1		0.047	0.047	0.286	0.047	0.047	0.161	0.169	0.047	0.047
>17	^{228}Th	0.002	0.002	0.013	0.002	0.002	0.007	0.008	0.002	0.002
12–17		0.002	0.002	0.013	0.002	0.002	0.007	0.008	0.002	0.002
7–12		0.003	0.003	0.015	0.003	0.003	0.009	0.009	0.003	0.003
2–7		0.003	0.003	0.019	0.003	0.003	0.011	0.011	0.003	0.003
1–2		0.005	0.005	0.028	0.005	0.005	0.016	0.016	0.005	0.005
≤1		0.038	0.038	0.230	0.038	0.038	0.129	0.136	0.038	0.038
>17	^{210}Pb	0.059	0.059	0.153	0.059	0.059	0.133	0.097	0.059	0.250
12–17		0.123	0.123	0.317	0.123	0.123	0.276	0.202	0.123	0.519
7–12		0.099	0.099	0.253	0.099	0.099	0.221	0.161	0.099	0.416
2–7		0.091	0.091	0.233	0.091	0.091	0.204	0.149	0.091	0.383
1–2		0.127	0.127	0.327	0.127	0.127	0.286	0.209	0.127	0.537
≤1		0.248	0.248	0.636	0.248	0.248	0.555	0.406	0.248	1.044

3.3. Statistical analysis

A comparison test (nonparametric-Kruskal Wallis test) of gross alpha, gross beta activity concentrations and TDS were performed for all sources of drinking water (TW, FW, CW, and BW). It was clear that gross alpha and beta activity concentrations in tap water were significantly higher than other water sources, where samples of tap water exceeded the recommended limits of 0.5 and 1.0 Bq L^{-1}, respectively [12,13]. On the contrary, gross alpha and beta activity concentrations for the rest of water samples, including home filtered water (by RO or IE), commercial cooler water, and bottled water were all below the maximum allowable limits. Based on these results, people should use filters at their homes or they can purchase plastic water dispenser bottles (commercial water) or bottled water (Fig. 4, Table 10).

Table 9
The estimated lifetime risk of natural radionuclides in Aqaba drinking waters from all sources with dose conversion factors D_{cf} (Sv Bq^{-1})

		^{238}U	^{234}U	^{230}Th	^{226}Ra	^{210}Pb	^{210}Po	^{232}Th	^{228}Ra	^{228}Th
D_{cf}		4.5×10^{-8}	4.9×10^{-8}	2.1×10^{-7}	2.8×10^{-7}	6.9×10^{-7}	1.2×10^{-6}	2.3×10^{-7}	6.9×10^{-7}	7.2×10^{-8}
TW		5×10^{-5}	5.2×10^{-5}	2×10^{-4}	2.9×10^{-4}	1.1×10^{-3}	1.3×10^{-3}	2×10^{-4}	1.1×10^{-3}	7.6×10^{-5}
FW		3.2×10^{-6}	3.5×10^{-6}	1×10^{-5}	2×10^{-5}	1×10^{-4}	8×10^{-5}	2×10^{-5}	1×10^{-4}	5.1×10^{-6}
CW		7×10^{-6}	7.6×10^{-6}	3×10^{-5}	4.4×10^{-5}	1.9×10^{-4}	2×10^{-4}	4×10^{-5}	2×10^{-4}	1.1×10^{-5}
BW	UT	2.6×10^{-6}	2.8×10^{-6}	1×10^{-5}	1.6×10^{-5}	1.1×10^{-4}	7×10^{-5}	1×10^{-5}	1×10^{-4}	4.1×10^{-6}
	AQ	2.6×10^{-6}	2.8×10^{-6}	1×10^{-5}	1.6×10^{-5}	1.1×10^{-4}	7×10^{-5}	1×10^{-5}	1×10^{-4}	4.1×10^{-6}
	GH	1.6×10^{-5}	1.7×10^{-5}	7×10^{-5}	9.8×10^{-5}	2.9×10^{-4}	4×10^{-4}	8×10^{-5}	3×10^{-4}	2.5×10^{-5}
	MF	2.6×10^{-6}	2.8×10^{-6}	1×10^{-5}	1.6×10^{-5}	1.1×10^{-4}	7×10^{-5}	1×10^{-5}	1×10^{-4}	4.1×10^{-6}
	RV	2.6×10^{-6}	2.8×10^{-6}	1×10^{-5}	1.6×10^{-5}	1.1×10^{-4}	7×10^{-5}	1×10^{-5}	1×10^{-4}	4.1×10^{-6}
	NJ	8.8×10^{-6}	9.6×10^{-6}	4×10^{-5}	5.5×10^{-5}	2.6×10^{-4}	2×10^{-4}	5×10^{-5}	3×10^{-4}	1.4×10^{-5}
	RS	9.3×10^{-6}	1×10^{-5}	4×10^{-5}	5.8×10^{-5}	1.9×10^{-4}	2×10^{-4}	5×10^{-5}	2×10^{-4}	1.5×10^{-5}
	AR	2.6×10^{-6}	2.8×10^{-6}	1×10^{-5}	1.6×10^{-5}	1.1×10^{-4}	7×10^{-5}	1×10^{-5}	1×10^{-4}	4.1×10^{-6}
	NT	2.6×10^{-6}	2.8×10^{-6}	1×10^{-5}	1.6×10^{-5}	4.8×10^{-4}	7×10^{-5}	1×10^{-5}	5×10^{-4}	4.1×10^{-6}

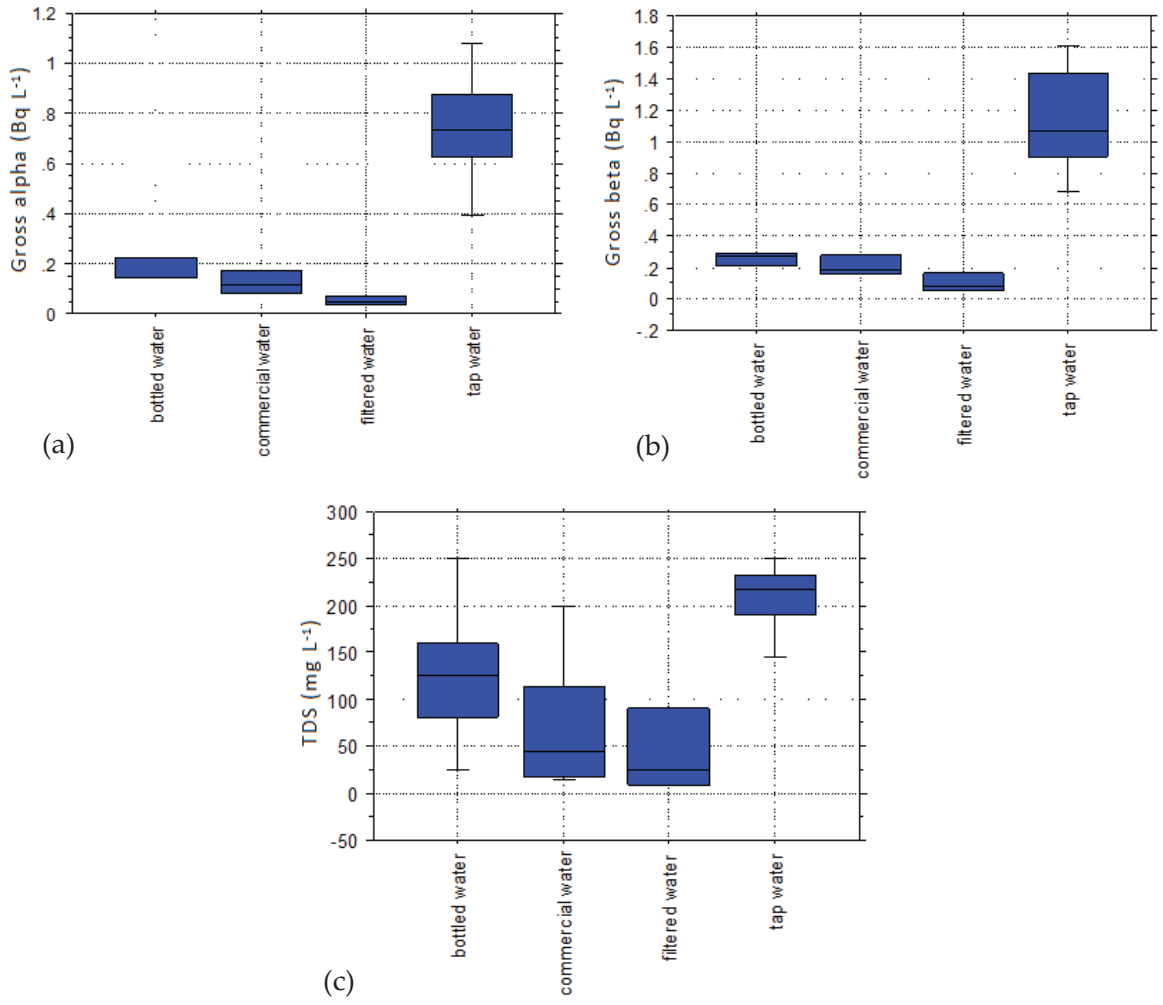

Fig. 4. Box-plot of (a) gross alpha, (b) gross beta activity concentrations and (c) TDS for all sources of drinking water (tap water, home filtered water, commercial water, and bottled water) in Aqaba city, Jordan.

The statistical test for TDS values for all water sources revealed that tap water was significantly higher than other sources (Fig. 4, Table 10). However, all TDS values for all water resources were below the maximum allowable limit (1,000 mg L^{-1}) according to the Jordanian standards [13].

The values of gross alpha and beta activity concentrations as well as annual effective doses of the present study were compared with other previous works worldwide (Table 11). It was noticed that the mean values of activities and doses in tap water from Aqaba were higher than the reported values by other studies at different locations.

4. Conclusions

Clean water is essential for healthy human life. The present study was performed to provide additional information about natural radioactivity levels in drinking water from different sources, to obtain an overall picture about the annual effective doses due to water consumption. This comprehensive study was conducted for the first time in Aqaba, Jordan. The activity concentrations data obtained exceeded the recommended limits of gross alpha and beta activities for the majority of tap water samples. Therefore, further investigations are highly recommended to determine the activity concentrations of specific radionuclides in tap water such as radium and uranium. The annual effective doses were also higher than the recommended RDL of 0.1 mSv from one year's consumption of drinking tap water. The risk levels of ^{226}Ra, ^{228}Ra, ^{210}Po, and ^{210}Pb from drinking tap water in Aqaba exceeded 10^{-4}. Infants and adolescents are the most vulnerable population groups since they receive the highest doses from drinking TW. No hazard is found from uranium exposure since the lifetime risk is much lower than 10^{-4} for all age groups through drinking water from all sources. It could be concluded that the radiological hazard associated with intake of radionuclides via drinking tap water is significant in the study area. Because of the high efficiency of filters in removing radionuclides from tap water, people should use filters at their homes in Aqaba. Alternatively, they can use plastic water cooler dispenser bottles (CW) or some brands of BW. For sustainable use of water resources, suitable purification method or methods should be used for this tap water in Aqaba.

Table 10
Comparison test (nonparametric – Kruskal Wallis test) of gross alpha, gross beta activity concentrations and TDS for all sources of drinking water (TW, FW, CW, and BW) in Aqaba city, Jordan

	P-Values (Kruskal Wallis test)		
	Gross alpha (Bq L^{-1})	Gross beta (Bq L^{-1})	TDS (mg L^{-1})
Among water sources	<0.0001	<0.0001	0.0002

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Table 11
Comparison between mean values or ranges of gross alpha and beta activity concentrations, and effective dose for the present study and other worldwide studies

Water type	Gross alpha (Bq L^{-1})	Gross beta (Bq L^{-1})	Effective dose (mSv y^{-1})	Country/City	Reference
Groundwater	NA	NA	0.001–2.375 (0.167)	Western Australia	Walsh et al., 2014 [36]
Rivers, dams, and boreholes	0.018–0.094 (≤0.5)	0.024–0.734 (≤1.0)	0.06[a] Due to U	South Africa	Manickum et al., 2014 [37]
Drilled wells	0.08–0.38 (0.192)	0.12–3.47 (0.579)	0.04–0.20	Turkey	Turhan et al., 2013 [11]
Tap, lake, spring, river, and mineral	68.11×10^{-3}	169.44×10^{-3}	(20.148–977.18)[a]	Turkey	Gorur and Camgoz, 2014 [9]
Surface water	$(0.45–1.36)\times10^{-3}$	0.061–0.279	Below WHO limits	Bangladesh	Biswas et al., 2015 [8]
Boreholes, and dug wells	0.0064–0.0182	0.046–0.126	0.0304–0.0678	Nigeria	Ogundare and Adekoya, 2015 [38]
Bottled water	<0.011–0.601	<0.026–0.695	ND	Mexico	Dávila Rangel et al., 2002 [39]
Groundwater	<0.01–0.035 (0.0149)	0.06–0.91 (0.3295)	ND	Nigeria	Garba et al., 2013 [40]
Groundwater and spring	0.01–19.5	0.13–6.6	ND	UAE and Oman	Murad et al., 2014 [31]
Tap water	$(<50–250)\times10^{-3}$	$(<188–327)\times10^{-3}$	0.15	Amman, Jordan	Al-Amir et al., 2012 [16]
WHO (2011)	0.5	1.0	0.1		WHO, 2011 [12]
JISM (2015)	0.5	1.0	0.5		JISM, 2015 [13]
Tap water (ground water)	0.301–1.188 (0.748)	0.604–1.626 (1.130)	0.722	Aqaba, Jordan	The present study

NA — not analysed; ND — not detected.
[a]Values reported in μSv y^{-1}

Jordan/Aqaba Branch to Riyad Manasrah to be spent at the Mote Marine Laboratory in Florida USA. Fulbright scholarship was also awarded to Riyad Manasrah during this period.

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