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ARTICLE

Dose from Naturally Occurring Radium Radioactivity in Abstracted Disi Fossil Groundwater*

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Abstract: The radium activity concentration data measured by Vengosh *et al.* [1] in water samples from the Disi aquifer are utilized to calculate the annual effective dose delivered to adult human consumers. Although the total activity in the Rum group in particular is significantly high compared to the very conservative World Health Organization WHO guidelines, the calculated average effective dose is slightly higher than the Jordanian standard and less than the corresponding value in the Australian guidelines. Blending models are suggested which reduce the dose and its associated risks. The results reveal the radiological quality of the indispensable Disi drinking-water to be satisfactory for consumption in a water-poor part of the World.

Keywords: Radioactivity; Disi aquifer; Disi conveyance project; Groundwater; Dose; Risk assessment.

PACS: 89.60.-k; 92.40.Kf; 92.40.kh; 92.40.kc; 67.63.-r; 67.80.F-

Introduction

Although Mediterranean countries are diverse in their socio-economic development, infrastructure, climate and water availability, the region as a whole is undergoing rapid social and environmental changes which may harbor negative implications for future sustainability [2]. Water scarcity is anticipated to become an even greater regional problem in the near future, as the population grows and climate change potentially makes precipitation more uncertain and variable. Jordan, in particular, has already one of the lowest levels of water resource availability per capita in the World. Management of water resources is therefore a key issue facing national government authorities [3, 4].

In July 2013, Jordan began pumping water from the southern fossil aquifer of Disi. A $990 million project started in 2009 which involves digging 55 wells and piping water supplies 325 kilometers to the capital city Amman, as well as to other governorates in the country. The lifespan of this non-renewable water conveyance project is estimated at 20-30 years, if abstraction rates are kept at around 100 mcm each year. The project hence provides a provisional solution to a long-term problem, but provides Jordan with enough time to consider other options like desalination [3]. Therefore, the Disi resource is of vital importance to the country, especially amid the unrest in the region which imposes direct multifold impacts on Jordan, one of which is related to hosting significant numbers of refugees.

In 2009, a study by Vengosh *et al.* [1] was conducted aiming at understanding how salinity is correlated with radioactivity in groundwater, to evaluate the sources of radium in the Disi aquifer, to investigate the possible mechanisms of radium mobilization from the host aquifer rocks and to evaluate the impact of this phenomenon on future water utilization from similar aquifer basins in the Middle East.

* A new analysis of the Vengosh *et al.* [1] data.

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Though the high radium content in the Disi aquifer in Central Jordan is hypothetically correlated to its high salinity, Vengosh *et al.* noticed that the corresponding high radioactivity in the Rum Group is associated with low-saline groundwater. In addition, this finding cannot be explained by anomalous radium content in the host aquifer rocks which are not different from those of other worldwide sandstone rocks.

The study ultimately revealed the Disi water to be highly radioactive, thus surrounding the Disi conveyance project with controversy. The paper [1] reported the combined ^{226}Ra and ^{228}Ra activities to be much higher than international drinking water standards. The reported data raised concerns over the safety of Disi and similar nonrenewable groundwater reservoirs, intensifying the already severe water crisis in the region. That important paper was cited in different reports [*e.g.* refs. 5-8] in addition to local and international media and became the focus of attention for a continued debate over the indispensable Disi conveyance project.

The activity concentration of three α-emitting isotopes of radium; namely ^{223,224,226}Ra, in addition to the β-emitting ^{228}Ra, were measured by Vengosh *et al.* [1] in thirty-seven groundwater samples collected, at different dates, from wells in the sandstone Disi aquifer. The study covered the Rum Group aquifer [9], the Khreim Group in Disi-Mudawwara [10] and areas in Central Jordan. The current work aims at a further analysis of the same raw data reported in Table 1 of the Vengosh *et al.* paper. In addition to radioactivity concentration, this work evaluates the committed effective annual dose from the four radium isotopes measured by Vengosh *et al.*. The results are then discussed in the framework of national and international guidelines and standards. The associated risks are finally assessed.

Results and Discussion

The hydrogeological nature of the Vengosh *et al.* [1] study did not require the calculation of the corresponding effective dose delivered to consumers. Therefore, Table 1 of the Vengosh *et al.* paper only lists the measured activity concentration (in Bq/l) for the four radium isotopes. Although the table compares these activity concentration values to the corresponding international requirements and guidelines, no dose calculation at that stage was implied by the objectives of the study.

In order to complement that earlier research, the quantity of interest in this work becomes the committed effective annual dose. It is calculated from the individual radionuclide concentration and the corresponding dose coefficient [11] for adults, assuming annual consumption of 730 liters [12]. The total dose is calculated as:

$$\left.\begin{aligned} & D_{Total}(mSv/a) = \\ & \sum_i D_i(mSv/a) = \\ & \sum_i A_i(Bq/l) \times 730(l/a) \times C_i(mSv/Bq), \end{aligned}\right\} \quad (1)$$

where D_i is the dose from a given isotope i, A_i is the activity concentration for each isotope as measured by Vengosh *et al.*, while the dose conversion coefficients C_i (Table 1) are obtained from the International Commission on Radiological Protection ICRP 2012 report [11], which are also adopted by the World Health Organization [12]. These dose coefficients account for radiation and tissue weighting factors, in addition to relevant metabolic information.

TABLE 1. The dose conversion coefficients for the four radium isotopes [11].

Isotope	C_i (mSv/Bq)
^{223}Ra	1 x 10^{-4}
^{224}Ra	6.5 x 10^{-5}
^{226}Ra	2.8 x 10^{-4}
^{228}Ra	6.9 x 10^{-4}

Data in Table 2 of this work was calculated using the corresponding data in Table 1 of Vengosh *et al.*. For each of the investigated wells, regular font data in the table are related to activity concentration, while bold font data are dose-related values. Private communication with the Water Authority of Jordan WAJ indicated that water currently pumped from the wells arrive at the reservoirs after a minimum period of 2.7 days. Though this period does not include an additional time to reach households through the distribution network, the 2.7 days period was adopted for a conservative estimate of the decay of the relatively short lived radium isotopes; namely ^{223}Ra and ^{224}Ra, with half-life times $T_{1/2}$ of 11.435 and 3.66 days [13], respectively.

Obviously, no significant decay is expected for the other two isotopes ($T_{1/2}(^{226}Ra)$=1600 years and $T_{1/2}(^{228}Ra)$=5.75 years [13]). Consequently, the activity concentration values in Table 2 (regular font) for ^{223}Ra and ^{224}Ra differ from the corresponding values in Vengosh *et al.*. In addition to these activity concentration values A_i, the corresponding dose from each isotope D_i (Eq. 1) is also tabulated in boldface.

It is evident that though the relative contribution of ^{224}Ra (a progeny of the relatively high abundant ^{232}Th) to the total activity concentration, and in general to the gross alpha activity, is significant (Table 1 in Vengosh *et al.*), its short half-life together with its relatively small conversion coefficient C_i (Table 1) cause its contribution to the total dose to diminish (Table 2 and Fig. 1). In addition, the activity concentration of ^{223}Ra, being a progeny of the much less abundant ^{235}U, is obviously small. This fact, together with its short half-life and relatively small C_i, yield a negligible contribution of this radium isotope to the total dose (Fig. 1). Table 2 and Fig. 1 reveal the fact that ^{228}Ra, being a progeny of ^{232}Th with long half-life and large C_i, dominates in terms of its contribution to the total dose. Finally, ^{226}Ra, a daughter in the ^{238}U decay series, contributes significantly to the total dose for reasons qualitatively similar to those related to ^{228}Ra, but with quantitatively smaller effect. In the above discussion, the half-life affects the dose in terms of the decay during the period between water withdrawal and consumption. On the other hand, the four radionuclides under consideration have the same biological half-life, and the reverse effect of decay half-life is accounted for by the dose conversion factors C_i.

The total activity concentration (in the reservoirs) and the corresponding dose value are calculated and listed in the seventh column of Table 2. The activity concentration screening levels of 0.5 Bq/l for gross alpha activity and 1 Bq/l for gross beta activity as set by the WHO [12] are obviously exceeded. Consequently, the dose from individual radionuclides should be considered (Fig.1). The total dose from the four Ra isotopes for each Disi aquifer group are histogrammed in Fig. 2. Obviously, the dose from the Rum Group as well as from Central Jordan wells is high compared to the 0.1 mSv/a recommended in the WHO Guidelines [12].

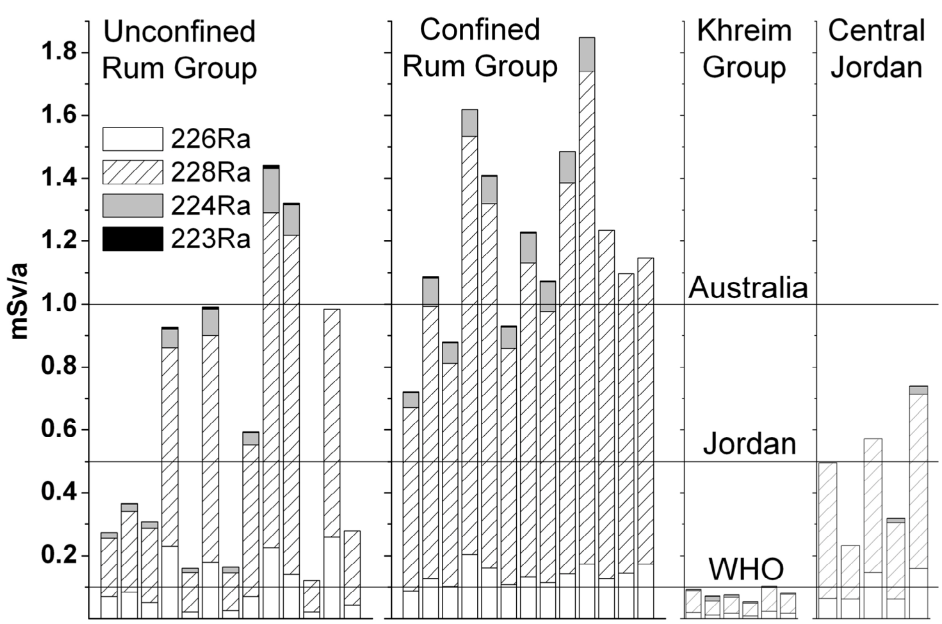

FIG. 1. The dose contribution of the four radium isotopes for each of the Disi aquifer groups. A conservative delay period of 2.7 days for water pumped from each well to reach the collection/mixing reservoir has been assumed.

TABLE 2. The data are based on data in Table 1 of Vengosh *et al.* [1]. The activity concentration after a conservative conveyance delay period of 2.7 days has been calculated for the four radium isotopes, together with the corresponding dose. The total dose is compared to the WHO guideline value of 0.1 mSv/a, to the Jordanian standard of 0.5 mSv/a, as well as to the Australian guideline of 1 mSv/a.

Area and well name	Well ID	^{226}Ra Bq/L **mSv/a**	^{228}Ra Bq/L **mSv/a**	^{224}Ra Bq/L **mSv/a**	^{223}Ra Bq/L **mSv/a**	Total Bq/L **mSv/a**	WHO Activity %[a] **Dose %[b]**	Jordanian **Dose %[b]**	Australian **Dose %[b]**
				Unconfined Rum Group					
Sahl El Suwan SS-6	ED1506	0.34	0.37	0.37	0.009	1.09	442		
		0.0695	**0.1864**	**0.0176**	**0.0007**	**0.2742**	**274**	**55**	**27**
Sahl El Suwan SS-5A	ED1505	0.41	0.51	0.51	0.023	1.45	604		
		0.0838	**0.2569**	**0.0242**	**0.0017**	**0.3666**	**367**	**73**	**37**
M 14 (Rum Co.)	ED1612	0.25	0.47	0.40	0.017	1.13	536		
		0.0511	**0.2367**	**0.0188**	**0.0012**	**0.3079**	**308**	**62**	**31**
Sahl El Suwan SS-4	ED1504	1.13	1.25	1.26	0.082	3.72	1497		
		0.2310	**0.6296**	**0.0598**	**0.0060**	**0.9264**	**926**	**185**	**93**
M 4 (Rum Co.)	ED1623	0.10	0.25	0.28	0.010	0.64	289		
		0.0204	**0.1259**	**0.0134**	**0.0007**	**0.1605**	**160**	**32**	**16**
SS20 (Sahl El Suwwan)	ED1614	0.88	1.43	1.77	0.103	4.18	1705		
		0.1799	**0.7203**	**0.0840**	**0.0075**	**0.9916**	**992**	**198**	**99**
M 5 (Rum Co.)	ED1624	0.12	0.24	0.38	0.010	0.75	291		
		0.0245	**0.1209**	**0.0179**	**0.0007**	**0.1641**	**164**	**33**	**16**
Mneisheer M6	ED1540	0.34	0.96	0.81	0.036	2.15	1079		
		0.0695	**0.4836**	**0.0384**	**0.0026**	**0.5941**	**594**	**119**	**59**
SS24 (Sahl El Suwwan)	ED1608	1.11	2.11	2.99	0.135	6.35	2534		
		0.2269	**1.0628**	**0.1420**	**0.0099**	**1.4416**	**1442**	**288**	**144**
Mneisheer W-2 /M 8	ED1402	0.69	2.14	2.07	0.062	4.96	2422		
		0.1410	**1.0779**	**0.0982**	**0.0045**	**1.3217**	**1322**	**264**	**132**
Qa Abu Suwana M2	ED1509	0.10	0.20			0.30	210		
		0.0204	**0.1007**			**0.1212**	**121**	**24**	**12**
Qa Disi well no. 3	QD3	1.27	1.44			2.71	1567		
		0.2596	**0.7253**			**0.9849**	**985**	**197**	**98**
Quweirah well no. 3	S5	0.21	0.47			0.68	491		
		0.0429	**0.2367**			**0.2797**	**280**	**56**	**28**
				Confined Rum Group					
Gramco G 6	K1034	0.43	1.16	1.00	0.031	2.62	1306		
		0.0879	**0.5843**	**0.0475**	**0.0022**	**0.7219**	**722**	**144**	**72**
Gramco G 3	K1031	0.62	1.72	1.91	0.058	4.31	1979		
		0.1267	**0.8664**	**0.0908**	**0.0042**	**1.0881**	**1088**	**218**	**109**

Area and well name	Well ID	^{226}Ra Bq/L **mSv/a**	^{228}Ra Bq/L **mSv/a**	^{224}Ra Bq/L **mSv/a**	^{223}Ra Bq/L **mSv/a**	Total Bq/L **mSv/a**	WHO Activity %[a] **Dose %[b]**	Jordanian **Dose %[b]**	Australian **Dose %[b]**
Gramco G 4	K1039	0.50	1.41	1.34	0.031	3.28	1597		
		0.1022	**0.7102**	**0.0638**	**0.0023**	**0.8785**	**878**	**176**	**88**
Wafa 3	K1043	1.00	2.64	1.81		5.45	2921		
		0.2044	**1.3298**	**0.0857**		**1.6198**	**1620**	**324**	**162**
Wafa 2	K1028	0.79	2.30	1.82	0.047	4.95	2565		
		0.1615	**1.1585**	**0.0862**	**0.0034**	**1.4096**	**1410**	**282**	**141**
Wafa 1	K1027	0.53	1.49	1.42	0.048	3.49	1690		
		0.1083	**0.7505**	**0.0675**	**0.0035**	**0.9298**	**930**	**186**	**93**
Arab Agriculture Co. 1	K1016	0.65	1.98	2.00	0.053	4.69	2251		
		0.1329	**0.9973**	**0.0951**	**0.0038**	**1.2291**	**1229**	**246**	**123**
Arab Agriculture Co. 3	K1020	0.56	1.71	2.03	0.043	4.34	1973		
		0.1145	**0.8613**	**0.0962**	**0.0032**	**1.0751**	**1075**	**215**	**108**
Arab Agriculture Co. 6	K1026	0.70	2.47	2.07		5.24	2747		
		0.1431	**1.2441**	**0.0982**		**1.4854**	**1485**	**297**	**149**
Suleiman MarI El Ataneh	K3023	0.85	3.11	2.29		6.25	3424		
		0.1737	**1.5665**	**0.1084**		**1.8487**	**1849**	**370**	**185**
Al-Arabiya well no. 9	K1041	0.62	2.20			2.82	2262		
		0.1267	**1.1081**			**1.2349**	**1235**	**247**	**123**
Suleiman Abu Juweied		0.71	1.89			2.60	1961		
		0.1451	**0.9520**			**1.0971**	**1097**	**219**	**110**
				Khreim Group					
Al Hodood well	11S1	0.09	0.14	0.07	0.003	0.31	157		
		0.0184	**0.0705**	**0.0034**	**0.0002**	**0.0926**	**93**	**19**	**9**
Fawwaz Jeryes El Halaseh (BH9)	ED1602	0.05	0.09	0.30	0.017	0.46	127		
		0.0102	**0.0453**	**0.0142**	**0.0012**	**0.0710**	**71**	**14**	**7**
Hasan Salameh El Hawashleh 1	ED3009	0.08	0.10	0.16	0.009	0.35	125		
		0.0164	**0.0504**	**0.0077**	**0.0007**	**0.0751**	**75**	**15**	**8**
Mohammad Odeh El Njadat	ED3008	0.04	0.08	0.10	0.007	0.22	94		
		0.0082	**0.0403**	**0.0046**	**0.0005**	**0.0535**	**54**	**11**	**5**
Halet Ammar 2 (HA2)/W16	K3000	0.11	0.15	0.10	0.004	0.36	171		
		0.0225	**0.0756**	**0.0046**	**0.0003**	**0.1029**	**103**	**21**	**10**
Halet Ammar 2 (HA2)/W16	K3000	0.08	0.12	0.07	0.003	0.27	135		
		0.0164	**0.0604**	**0.0034**	**0.0002**	**0.0804**	**80**	**16**	**8**
				Central Jordan					
Lajjun deep well	Lajjun	0.31	0.86			1.17	891		
		0.0634	**0.4332**			**0.4966**	**497**	**99**	**50**

Area and well name	Well ID	^{226}Ra Bq/L **mSv/a**	^{228}Ra Bq/L **mSv/a**	^{224}Ra Bq/L **mSv/a**	^{223}Ra Bq/L **mSv/a**	Total Bq/L **mSv/a**	WHO Activity %[a] **Dose %[b]**	Jordanian **Dose %[b]**	Australian **Dose %[b]**
Potash well 2-TA2	DA1039	0.30	0.34			0.64	370		
		0.0613	**0.1713**			**0.2326**	**233**	**47**	**23**
Potash well 1-TA1	DA3023	0.72	0.84			1.56	912		
		0.1472	**0.4231**			**0.5703**	**570**	**114**	**57**
Potash well 1-TA1	DA3023	0.30	0.48	0.31	0.013	1.10	542		
		0.0613	**0.2418**	**0.0148**	**0.0009**	**0.3188**	**319**	**64**	**32**
Potash well 2-TA2	DA1039	0.78	1.10	0.52	0.024	2.42	1232		
		0.1594	**0.5541**	**0.0245**	**0.0017**	**0.7397**	**740**	**148**	**74**

[a] Percent values of the recommended activity concentration by the WHO [12]): [^{226}Ra activity + (^{228}Ra activity/0.1) + ^{224}Ra activity + ^{223}Ra activity] x 100;
[b] Percent values of the recommended dose.

TABLE 3. The average radium dose of the four Disi aquifer groups, their overall average and combinations of them. Blending with non-Disi waters with two different ratios could reduce the overall average dose to levels below the Jordanian limit.

	Dose (mSv/a)		
Group	Pure Disi	Mixing 1:1[a]	Mixing 2:1[b]
Unconfined Rum	0.61 ± 0.47	0.38 ± 0.23	0.46 ± 0.31
Confined Rum	1.21 ± 0.31	0.68 ± 0.16	0.86 ± 0.21
Khreim	0.08 ± 0.02	0.11 ± 0.01	0.10 ± 0.01
Central Jordan	0.47 ± 0.20	0.31 ± 0.10	0.36 ± 0.13
Average for all groups	0.59 ± 0.15	0.37 ± 0.07	0.45 ± 0.10
Ave. Rum and Khreim	0.63 ± 0.19	0.39 ± 0.09	0.47 ± 0.12
Ave. Rum	0.91 ± 0.28	0.53 ± 0.14	0.66 ± 0.19
Ave. Unconfined Rum and Khreim	0.34 ± 0.23	0.25 ± 0.12	0.28 ± 0.16

A conservative fixed non-Disi dose of 0.15 mSv/a was adopted [6], therefore: [a] the uncertainty is the statistical uncertainty of the Disi group(s) × $^1/_2$; [b] the uncertainty is the statistical uncertainty of the Disi group(s) × $^2/_3$.

In addition, and since consumption of radium in drinking water increases the risks for bone cancer and leukemia, it is important to note that “many” Rum-group wells exceed the derived concentration of 0.5 Bq/l (or 1 Bq/l) for ^{226}Ra and “most” Rum-group wells exceed the derived concentration of 0.2 Bq/l (or 0.1 Bq/l) for ^{228}Ra, as set by the European Union [14] (or in the WHO guidelines [12]). The combined ^{226}Ra and ^{228}Ra activities also exceed the US-EPA limit of 5 pCi/l [15]. Consequently, the committed effective annual dose from individual radionuclides should be considered (Fig.1). Obviously, the annual dose from the Rum-Group as well as from Central Jordan wells is high compared to the 0.1 mSv/a recommended in the WHO Guidelines. It is worth mentioning that in October 2013, the European Union [14] adopted the same WHO guideline value of 0.1 mSv/a. The above mentioned guidelines on activity concentration of 1 Bq/l and 0.1 Bq/l for ^{226}Ra and ^{228}Ra, respectively, are derived from this recommended dose of 0.1 mSv/a.

Nevertheless, the very same WHO report emphasizes the fact that "it is essential that each country reviews its needs and capacities in developing its regulatory framework". It also mentions that no international standards for drinking water quality are promoted for adoption, the main reason being "the advantage provided by the use of a risk-benefit approach, qualitative or quantitative, in the establishment of national standards and regulations". According to the report, the guidelines provide a scientific point of departure for national authorities to develop drinking water regulations and standards appropriate to the national situation. In particular, Chapter 9 of the WHO report that particularly discusses radiological aspects emphasizes that "screening levels and guidance levels are conservative and should not be interpreted as mandatory limits. Exceeding a guidance level should be taken as a trigger for further investigation, but not necessarily as an indication that the drinking-water is unsafe". The WHO report also emphasizes the fact that background radiation exposures vary widely across the Earth, but the average is about 2.4 mSv/a, with the highest local levels being up to 10 times higher without any apparent health consequences; 0.1 mSv therefore represents a small addition to background levels.

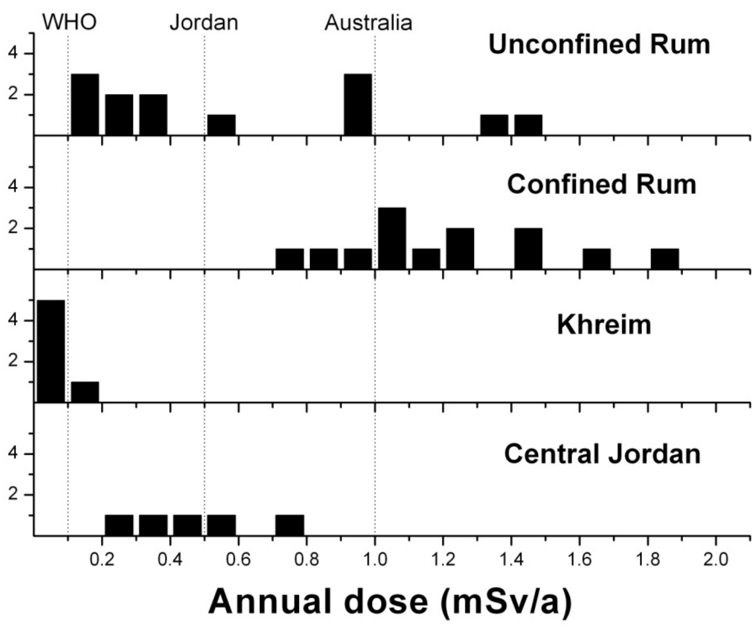

FIG. 2. A histogram of the radium dose from each well in the four Disi aquifer groups, compared to the WHO, Jordanian and Australian guidelines and standards.

In this context, the Australian National Water Quality Management Strategy report; namely the 2011 Australian Drinking-Water Guidelines [16], recommends a guideline dose of 1 mSv per year to be applied for radioactivity in drinking water. This is ten times the corresponding 2011 WHO value of 0.1 mSv/a [12]. The Australian document does not consider its recommended dose as a mandatory limit, but when exceeded, a decision on the need for and the degree of remedial action should be based on a cost-benefit analysis, and there may be circumstances where there is no practical alternative but to accept a dose that exceeds the guideline dose of 1 mSv/a. The Australian guideline value is based on earlier studies [17,18] on drinking water quality in areas dependent on groundwater. In Jordan, however, a mandatory regulation sets a standard of 0.5 mSv/a [19].

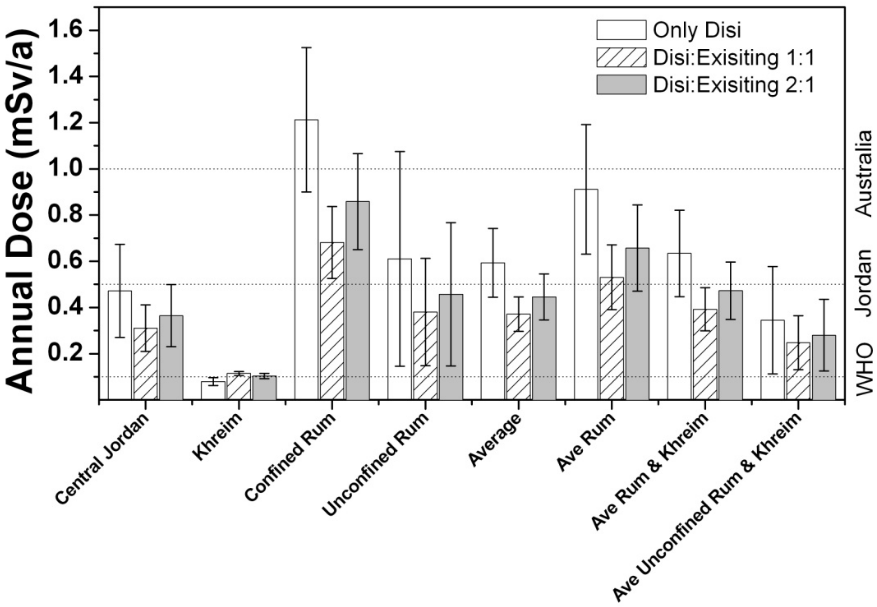

FIG. 3. Average radium dose according to two mixing models with non-Disi water with a conservative 0.15 mSv annual dose [6].

Therefore, in addition to the WHO guideline, both Australian guideline and Jordanian standard values are indicated in Figs. 1 and 2. The average dose from each group, together with its uncertainty, are depicted in the white column of Fig.3 (see Table 3). Water from the Khreim group could comply with the conservative WHO recommendation when the other less significant radionuclides are accounted for, while the average dose from Central Jordan wells could satisfy the Jordanian standard. The unconfined and confined Rum groups slightly exceed the Jordanian dose limit and the Australian guideline, respectively.

Needless to say, water treatment could considerably reduce radium concentration and hence the associated dose to levels well below the Jordanian standard. An alternative cost-effective solution is to develop a crude model for blending Disi ground-water with *e.g.* surface water in a reservoir in *e.g.* Amman. This is intended to provide an assessment, at least qualitatively, about the effectiveness of such mixing on reducing the dose in drinking water delivered to consumers. To make this model as conservative as possible, a dose value of 0.15 mSv/a will be adopted for the non-Disi resource [6]. Mixing ratios of Disi:Non-Disi =1:1 and 2:1 are considered (Table 3) and depicted in the shaded and gray columns of Fig. 3, respectively. According to such conservative models, a dose of less than the WHO guideline is definitely not achievable. Nevertheless, blending can reduce the dose well below the Jordanian standard.

Associated Risk Assessment

The linear-no-threshold LNT hypothesis [20-22] assumes that the demonstrated relationship between radiation dose and adverse effects at high levels of exposure can be linearly extrapolated to low levels relevant to drinking water, hence providing the "deliberately conservative" basis of radiation protection standards. Some evidence suggests that there may be a threshold below which no harmful effects of radiation occur. However, this is not yet accepted by radiation protection bodies as sufficiently well proven to be taken into official standards. Hence, the rather conservative LNT hypothesis is adopted in this assessment. Using LNT, the International Commission on Radiological Protection ICRP estimates the lifetime risk of a fatal cancer resulting from exposure to radiation to be 5×10^{-2} per Sv of annual radiation dose [16,23,24]. Fig. 4 depicts this linear relation in the relevant dose region of this study. On the basis of this estimate, a dose of 0.1 mSv per year gives a lifetime risk of about five additional fatal cancers per million people. The term "additinal fatal cancers" means incidences that occur in addition to those resulting from all other causes. The above discussion concentrated only on fatal cancer risks. The WHO documentation [12], on the other hand, considers the nominal probability coefficient for radiation-induced stochastic health effects, which include fatal cancer, non-fatal cancer and severe hereditary effects for the whole population to be 7.3×10^{-2} Sv^{-1} (which also refers to ICRP). Multiplying this by the annual dose yields the dashed line in Fig.4.

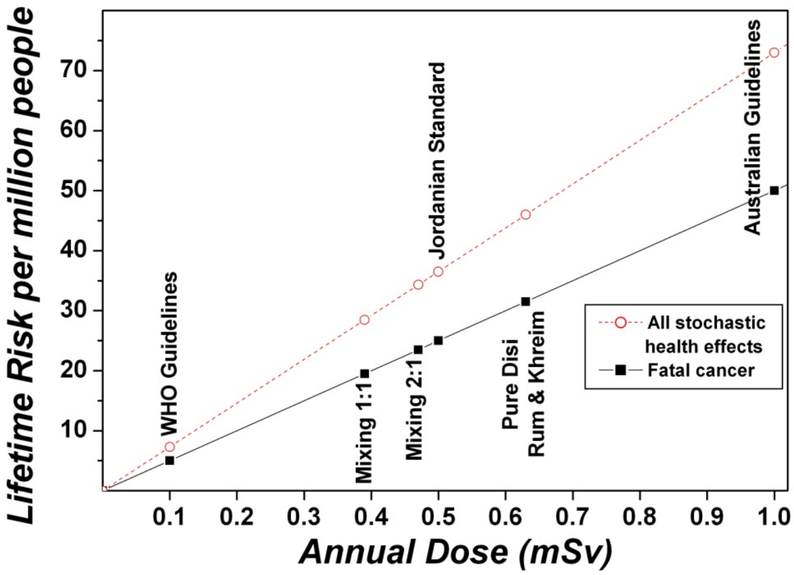

FIG. 4. Lifetime fatal cancer risks as well as all stochastic radiation-induced health effects per million people as a function of the annual radiation dose. Obviously, the conservative LNT hypothesis has been adopted. In calculating the average dose from pure Disi water, as well as for the two blending models, the Central Jordan wells have been excluded (Table 3), since water is assumed to be pumped from Rum- and Khreim-like wells.

It is worth emphasizing here that this study includes only radium isotopes. However, some guidelines and standards exclude radon and radon progeny, tritium, ^{14}C and ^{40}K from the calculation related to the limit of the total ingested dose. Among radon daughters, the β-emitter ^{210}Pb and α-emitter ^{210}Po with C_i values of 6.9×10^{-4} $mSvBq^{-1}$ and 1.2×10^{-3} $mSvBq^{-1}$, respectively, are worth particular attention. Though their dose conversion coefficients are high, being progenies of the gaseous radon, their corresponding activity concentration is remarkably low compared to radium in abstracted groundwater [7, 25]. The isotopic species in the natural decay series that belong to the elements thorium and protactinium can be neglected when groundwater safety is discussed, since both elements exhibit very poor aqueous solubility [26]. Uranium isotopes have relatively small C_i values [11]; namely 4.5×10^{-5} $mSvBq^{-1}$ for ^{238}U and 4.9×10^{-5} $mSvBq^{-1}$ for its grand-daughter ^{234}U (compare Table 1), and ^{235}U is poorly abundant. In general, uranium chemical toxicity is addressed separately.

Nevertheless, a comprehensive rigorous risk assessment should include all radionuclides; the above cited literature [*e.g.* ref. 7] indicates a possible conservative contribution of isotopes other than radium of about 5% to 25% to the total effective dose. Of particular importance is ^{210}Po [27]. Age-related doses should also be considered in a more comprehensive risk assessment. Finally, risk assessment should consider all radiological, chemical and biological factors, balanced against risks associated with deficiency in water supplies.

Conclusions and Recommendations

This work has been motivated by the necessity to provide further analysis of the data published by Vengosh *et al.* [1]. Though the author prepared a short comment on that paper, which has been recently published in the same journal [28], this work provides a more comprehensive analysis and discussion than provided in that short correspondence [28].

The results of this work reveal the radiological quality of the indispensable Disi drinking-water to be satisfactory for consumption in a water-poor part of the World, if risks are carefully managed. Blending ratios should take into consideration any possible buildup of the non-mobile ^{228}Th in the system, which could affect the ^{224}Ra concentration. Continuous and routine monitoring, including sample collection and measurement, is essential to ensure compliance with the local standards.

Transparency in the governmental water policies psychologically enhances the public acceptance. Practically, decision on blending ratios should always take into consideration the importance of reducing risk as much as reasonably achievable. However, the availability and quality of surface water, to a given blending reservoir, could be a limiting factor. Water treatment facilities, if found feasible, should be considered locally in regions with limited availability of surface water resources. Proposals for water desalination in the Gulf of Aqaba, which is intended to provide a more sustainable supply, can be considered as a future resource for blending which can take place on-site in the south, thus eliminating the necessity for regional blending. This scenario enables freeing surface water resources to be available to other usage.

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