Blending as the best compliance option for the management of radioactivity in drinking water supplied from the deep sandstone aquifer in Southern Jordan

Hazim K. El-Naser, Barry Smith, Susan Kilani, Ismail Abdeldin,
Barry Howarth and Bassam Saleh

ABSTRACT

This paper describes management options and interventions taken by the Government of Jordan to ensure that the quality of drinking water supplied to consumers via the Disi Water Conveyance Project (DWCP) meets Jordanian drinking water standards and WHO guidelines for drinking water quality in respect of their radiological composition. Results from an initial survey of radioactivity present in water abstracted from each of the 55 wells (which comprise the operational well field) indicated an average radiological dose of 0.8 milliSieverts per year (mSv/y) would be accrued by members of the population if consuming water directly from the well head. During full scale operation, the estimated accrued dose from the well field as a whole decreased to an average of 0.7 mSv/y which was still approximately 1.4 times the Jordanian reference radiological limit for drinking water (0.5 mSv/y). Following assessment of treatment options by relevant health and water authorities, blending prior to distribution into the consumer network was identified as the most practicable remedial option. Results from monthly sampling undertaken after inline blending support the adoption of this approach, and indicate a reduction in the committed effective dose to 0.4 mSv/y, which is compliant with Jordanian standards.

Key words | Disi project, drinking water quality, guidelines and standards, natural radioactivity, Ram aquifer, water treatment

Hazim K. El-Naser
Susan Kilani
Ismail Abdeldin
Bassam Saleh
Ministry of Water and Irrigation,
Shmisani, Jaber Bin Hayan Str,
PO Box 2412 Amman,
11183 Jordan

Barry Smith (corresponding author)
Intelliscience Ltd,
38A Station Rd,
Carlton,
Nottingham NG4 3DB,
UK
E-mail: *b.smith@intelliscience.co.uk*

Barry Howarth
SWECO,
Gjörwellsgatan 22,
PO Box 34044,
Stockholm SE-100 26,
Sweden

INTRODUCTION

Jordan is facing a future of very limited water resources. In 2010, these equated to a per capita share of water of $<147\ \mathrm{m}^3$ per year (Jaber & Mousa 2001; Humpal *et al.* 2012) whilst current data from the Jordanian Ministry of Water and Irrigation (MWI) indicate a per capita share of $130\ \mathrm{m}^3$/y. These per capita shares are in the lowest quartile of worldwide country specific water resources. If this supply remains constant, the yearly per capita domestic consumption is projected to fall to approximately $90\ \mathrm{m}^3$ by 2025, putting Jordan in the category of having an absolute water shortage that will constrain economic growth and potentially endanger public health (Mousa 2007; El-Naser 2009). Groundwater is the major domestic water supply source for most population centers of Jordan, but aquifers are already exploited above their safe yields (Humpal *et al.* 2012). In response to this situation, Jordan has adopted a strategy of extending its current small-scale abstraction of fossil groundwater from the Ram aquifer, which has been projected to be able to provide 100–125 million m^3/y of high-quality water over the next 50 years (El-Naser 2009; Humpal *et al.* 2012).

The Ram aquifer system (also commonly referred to as the Disi aquifer system in Jordan and the Saq aquifer system in Saudi Arabia) is a transnational aquifer exploited by the Kingdom of Jordan in the east and Kingdom of Saudi Arabia to the west (Figure 1). It is principally

doi: 10.2166/wh.2016.265

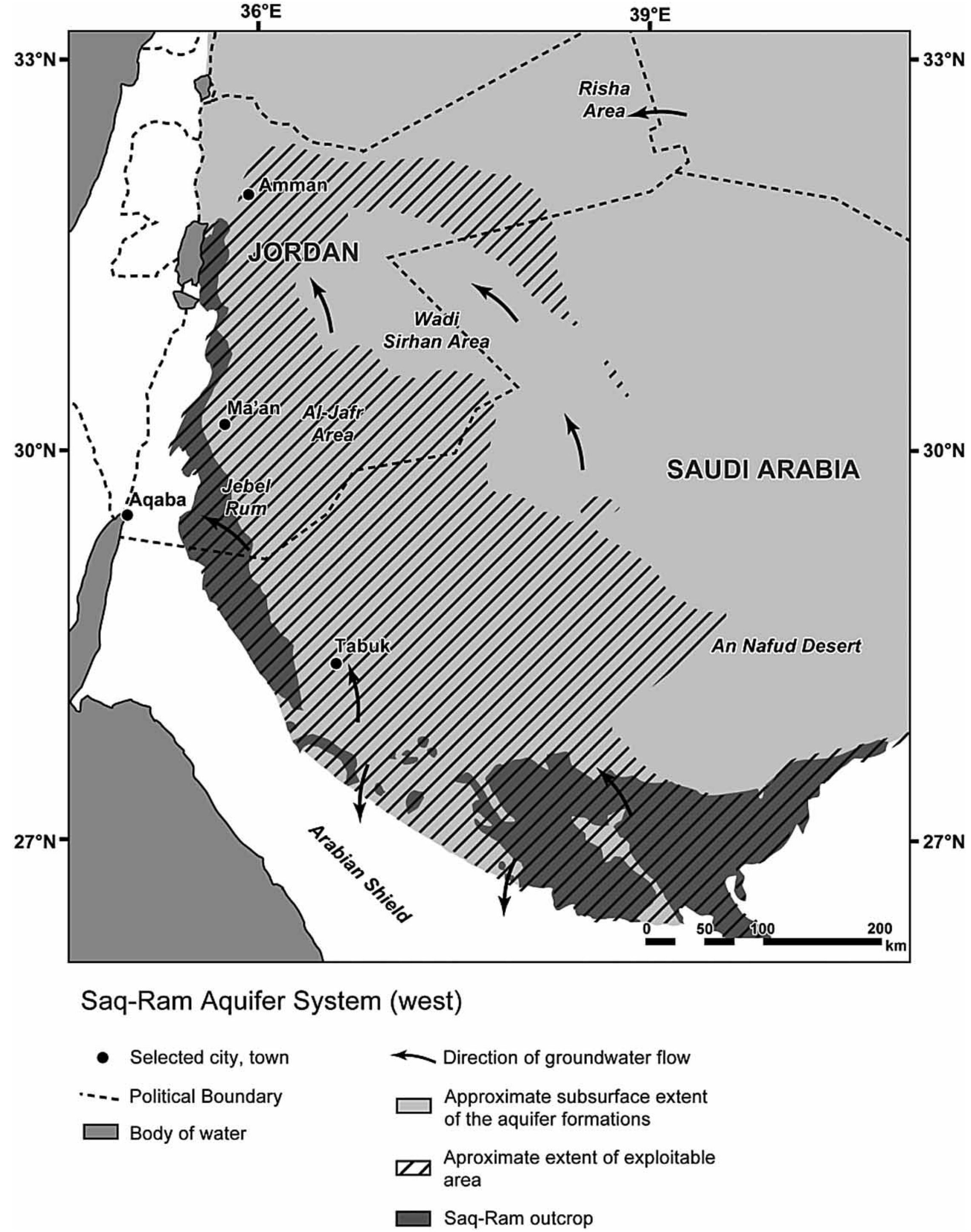

Figure 1 | Regional map showing the extents of the confined and unconfined Ram aquifer (adapted from: UN-ESCWA and BGR, 2013. Inventory of shared water resources in Western Asia, Beirut, Lebanon).

comprised of the Ram aquifer, which is distributed throughout the Umm Sham, Disi and Umm Ishrin sandstones (Supplementary Figure S1, available with the online version of this paper). It has been used as a local source of water in Jordan for the past 30 years, during which approximately 20 million m^3/y has been used to meet the water demand in the

Aqaba Zone of southern Jordan and about 60 million m^3/y has until recently been used for agricultural activities and the supply of local settlements. However, in 2014 the Government of Jordan (GoJ) made a decision to curtail the use of Disi water by agriculture to protect the aquifer from overexploitation and to secure drinking water for the coming generations. As a result of these changes, the total abstraction of Disi water for irrigation and local settlements was brought down from 60 to 12 million m^3/y.

Despite being of fossil origin (i.e. being derived from recharge occurring between 7,000 years before present (BP) in the unconfined part of the aquifer and 30,000 years BP in the confined areas) surveys of water quality within the Ram aquifer during these phases of abstraction and early well field development have demonstrated the water to be of high potable quality (El-Naser 2009). The excellent water quality is considered to be a function of the depth of the aquifer, the chemical purity of the host rock and current land use, all of which prevent and/or reduce contamination by pathogenic bacteria, viruses and human activities.

The main beneficiaries of the Disi Water Conveyance Project (DWCP) project are the capital Amman and the Zarqa Governorate, which traditionally have been the country's most water-stressed regions. Already, as a direct result of the DWCP, complaints regarding water supply (i.e. insufficient quantity) in these governorates have been reduced by over 80% and the duration of supply to domestic properties in the Amman increased from about 30 to 60 hours per week. It is also predicted that the supply of Ram aquifer water to these governorates will similarly lead to improved water quality and quantity. Other governorates such as Madaba and Karak that originally supplied large quantities of water to Amman can now reallocate these volumes to meet high demand during the summer months within their own areas. Within the coming two years, it is envisaged that the necessary trans-governorate transmission lines will be completed, where additional amounts of improved local resources in Zarqa and Mafraq will be available for blending with the Ram aquifer water, making the DWCP a truly national water conveyor of safe drinking water from the south west through Amman and then to the north of Jordan (El-Naser 2009).

Whilst the quality of water from the Ram Aquifer has been proven to be of good biological and chemical quality, increased international awareness of the abundance of naturally occurring radioactive substances (radionuclides) in groundwater (Cothern 1987; Smith *et al.* 1998; Tayyeb *et al.* 1998), from the Amman Zarqa basin (Gedeon *et al.* 1994a, 1994b; Powell & Smith 2011) and the publishing of the Jordanian drinking water standards during 2001 (JS 2001) led the Water Authority of Jordan (WAJ) and the Jordanian MWI to investigate the presence of radioactivity in waters from the Ram aquifer as part of the DWCP.

Upon detection of elevated levels of natural radioactivity in the Ram Aquifer during the development phase of the DWCP, the GoJ requested technical and normative guidance from the World Health Organization (WHO) through letters sent by the Minister of Health and the Minister of Water and Irrigation between 2006 and 2007 to the WHO Regional Centre for Environmental Health Action (CEHA), exchanging the results of investigations performed in 2003 and 2005 and means of managing the elevated levels of radioactivity (MWI/WAJ/MoH 2006). Data reported included the analysis of gross alpha and gross beta activities of well-head samples, and showed a wide range of activities (Table 1). Comparison with the Jordanian standard at that time (JS 2001) showed that over 85% of the samples exceeded the gross alpha and beta reference limits (0.5 Bq/l and 1.0 Bq/l, respectively).

Measured gross alpha and gross beta activities were consistent with activities of ^{226}Ra determined in waters from the Ram aquifer which ranged from 0.11 to 0.98 Bq/l. These data correspond to a yearly dose from 0.02 to 0.20 mSv/y based solely on the activity of ^{226}Ra (assuming the water had been consumed at the point of sampling). A parallel unpublished study also reported to WHO via CEHA investigated the contribution made by individual radionuclides to the total estimated radiological dose incurred by an adult

Table 1 | Concentrations of gross alpha and beta activity in sampled well waters from boreholes abstracting water from the Ram aquifer measured by WAJ/MWI during 2005

	Gross alpha (Bq/l)	Gross beta (Bq/l)
Maximum	7.1	5.6
Minimum	0.10	0.16
Average	1.9	2.3
% exceeding Jordanian drinking water guidelines (JS 2001)	98%	85%

drinking such water. During the period of this study, analysis for ^{226}Ra, ^{224}Ra, ^{238}U, ^{234}U, ^{228}Th, ^{228}Ra and ^{210}Pb were performed by internationally accredited laboratories (Becquerel Laboratories Inc. (Canada), Scientifics Ltd (UK) and AEA Technology Plc (UK)). The results from the study indicated that the greatest contributors to overall estimated dose were ^{228}Ra followed by ^{226}Ra and then ^{210}Pb.

On the basis of these data, which demonstrated exceedance of the JS 2001 and the WHO *Guidelines for Drinking Water Quality* (WHO 1993), the WAJ/MWI report to WHO/CEHA concluded that corrective measures should be considered for the drinking water supplied from the Ram aquifer (or indeed any other waters containing elevated concentrations of naturally occurring radionuclides). These measures included but were not limited to the following:

- Conducting further studies and investigations regarding radiological water quality in the Ram aquifer.
- Conducting health assessment studies.
- Cost–benefit analysis of treatment options including but not limited to blending with other water sources and active treatment using reverse osmosis and lime softening.
- Performing investigations into the viable waste management of radioactive residue from active treatment.
- Evaluating if the existing Jordanian Drinking Water Standard for radioactivity could be revised to better enable appropriate authorities to manage situations where elevated levels of radioactivity are encountered in drinking water.

WHO/CEHA, in its response to the MWI/WAJ (WHO/CEHA 2007), presented the outcomes of WHO's review of the results of the radiological quality of water abstracted from the Ram aquifer and the national interventions planned by WAJ/MWI. The observations were as follows:

- WHO guidelines for drinking water quality are advisory and not mandatory. Countries are encouraged to develop their own standards based on careful review of the prevailing environmental, social and economic conditions.
- The choice of national approach to managing a specific risk in drinking water quality is entirely a national decision.
- Exceeding the screening level 0.1 mSv/y does not necessarily mean the water is unsafe for drinking, but further investigation is required into the radionuclide composition of the water.
- WAJ estimate the annual contribution of ^{228}Ra and ^{226}Ra to be about 0.6 mSv/y (in the well field); this should be compared to the normal background levels from all internal and external sources of radiation exposure, which typically range from 1 to 10 mSv/y. This therefore, does not represent a significant increase in overall health risk from radiation exposure. This conclusion would not justify immediate corrective action.
- Raising the effective screening dose in Jordan from 0.1 to 0.5 mSv/y is based on a conviction that the potential health risks brought about are tolerable and that the net health benefits outweigh the potential health risks. The MWI/WAJ approach to the issue is quite reasonable, and not in contradiction with the guidance provided in the WHO guidelines for drinking water quality regarding the radioactivity guideline values.
- The remaining procedures described under the recommendations seem appropriate and logical.

More recent independent investigations (BRGM 2008; Vengosh *et al.* 2009) and subsequent press articles (Becker 2012; Wardam 2013) have caused a high degree of public concern and debate in Jordan, with the potentially frightening conclusions that the water in the Ram aquifer in Jordan contains combined ^{228}Ra and ^{226}Ra concentrations up to 2,000% higher than international drinking water standards and that the water if consumed would be detrimental to human health and may directly lead to severe health effects, including many forms of cancer, and that remedial measures would be inadequate. These conclusions, as this paper will demonstrate, were overly pessimistic.

To follow up their conclusions from previous investigations, and in the light of the more recent studies (e.g. Schubert *et al.* 2011) and those highlighted above, WAJ/MWI have undertaken additional studies to: (a) better quantify the presence of natural series radionuclides in Ram aquifer waters; (b) define appropriate mitigation strategies; and (c) join with the appropriate health protection and regulatory bodies in Jordan in interpreting Jordanian regulatory standards for the presence of naturally occurring radioelements in drinking water.

This paper reports the outcomes of these investigations and provides an assessment of the following:

- Naturally occurring radionuclide concentrations in 55 water supply and nine aquifer monitoring wells associated with the DWCP prior to and during active operation.
- Proposed mitigation options from the perspective of actual measured outcomes.
- Compliance against Jordanian standards for drinking water quality both at the well-head and as close as practicable to the point of actual public consumption.

METHODOLOGY

The well field

In Jordan, the unconfined portion of the Ram aquifer covers a total area of over 3,000 km^2 under the southern desert (Lloyd & Pim 1990; Schubert *et al.* 2011). In contrast, the confined aquifer extends under the majority of the country to the north and east of the DWCP well field, where it is overlain by Hiswa, Dubaidab and Holocene shales and sediments (Figure 1 and Supplementary Figure S1; all Supplementary Figures and Tables are available with the online version of this paper).

The DWCP well field (Supplementary Figure S2) occupies an approximate area of 400 km^2 in the Disi and Mudawara districts of Jordan and abstracts water from the confined and unconfined Ram aquifer. The aquifer water conveyed to Northern Jordan is the subject of this work. The main geological formations underlying the well field (Supplementary Figures S1 and S3) and forming the aquifer are the Cambro-Ordovician sandstone of the Umm Sahm, Disi and Umm Ishrin sandstone formations of the Ram group in Jordan (Lloyd & Pim 1990; Buckle 1993). In Saudi Arabia, these geological features correspond to the Saq formation (Lloyd & Pim 1990; BRGM 2008; Powell *et al.* 2014).

Examination of siliciclastic aquifer host rocks of the Ram aquifer at outcrop, in drill cuttings and by down hole gamma logging (Supplementary Figure S3) reveals that these host rocks exhibit on average a comparatively low level of total gamma response when unconfined. However, superimposed on this overall picture are a series of narrow (typically <5 m) horizons in the lower, middle and upper Disi sandstones) (Supplementary Figure S3; Powell *et al.* 2014) which exhibit a high total gamma response indicative of the presence of elevated concentrations of the naturally occurring radioactive elements (U, Th, and K) and members of their decay chains. The situation appears to be more complex when the aquifer begins to be confined, with elevated levels of total gamma response being observed throughout the Upper and Lower Hiswa (both mudstone and sandstone facies) and, to a more limited extent, within the Dubaidab formation, which is the host rock to the Khreym aquifer group. It has been surmised that these formations, which have been observed to contain abundant thorium-enriched heavy mineral aggregations, may be the source of the radioactive elements found in the deeper Ram aquifer, although this still remains a conjecture. An equally plausible explanation for the presence of bands of enhanced gamma emission and the presence of radioactivity in the waters of the Ram aquifer includes the presence of marine shales that formed during brief estuarine incursions into the Ram group (Powell, pers. comm. 2014).

Production wells (Table 2 and Supplementary Figure S2) were typically drilled to depths between 450 and 550 m below ground level (bgl) and completed with casing to around 300 m bgl on average. The producing portions (typically >300 m bgl) of the wells were either screened or left open hole depending on the prevailing aquifer properties. Following drilling and casing, the wells were developed by airlift/backwashing and jetting and then a combination of high rate pumping, step drawdown and constant rate pumping tests for over 24 hours. At the beginning and end of the constant rate pumping, samples were taken for hydrochemical analysis (non-radiological). At the end of well development, each production well (with the exception of five low productivity wells) had a final sustainable production rate of >70 l/s. To date, production wells in the well field have typically been pumping at a rate of between 70 and 80 l/s. This yields a total potential well field production rate of approximately 4,000 l/s or 132 million m^3/y.

Sampling

Sampling of the well field for the purposes of establishing levels of radioactive substances was initially undertaken between 2011 and 2013 during well field construction and

Table 2 | Results of the 55 wells for the radiological parameters of concern from the initial pre-commissioning survey of wells contributing to the DWCP

				Gross α (Bq/l)	Gross β (Bq/l)	^{226}Ra (Bq/l)	^{228}Ra (Bq/l)	^{210}Pb (Bq/l)
				Estimated uncertainty (Supplementary Table S2)				
	Well name	Operating flow rate (m^3/hr)	Total well depth (m)	5.8%	7.94%	9.39%	16.0%	5.60%
1	P1	289	530	0.87	4.53	0.40	1.87	0.02
2	P2	274	550	2.73	5.90	0.64	3.06	0.05
3	P3	259	550	1.20	2.47	0.51	2.02	0.12
4	P4	285	550	1.95	3.47	0.40	2.46	0.10
5	P5	290	560	0.45	1.83	0.47	1.87	0.06
6	P6	291	551	0.58	2.03	0.51	2.10	0.10
7	P7	290	550	3.17	5.27	0.64	2.78	0.10
8	P8	289	550	2.30	4.34	0.61	1.56	0.01
9	W1	288	532	1.57	3.10	0.67	1.32	0.03
10	W2	232	556	2.95	4.99	0.61	1.44	0.10
11	W3	268	501	1.49	2.40	0.24	0.40	0.30
12	W4	289	550	1.26	2.49	0.43	1.60	0.03
13	W5	289	500	1.54	2.70	0.37	1.07	0.06
14	W6	288	415	1.02	2.33	0.20	0.75	0.02
15	W7	287	550	3.13	2.97	0.15	0.99	0.01
16	W8	245	551	1.56	3.86	0.53	2.34	0.15
17	W9A	216	560	5.15	6.46	0.92	2.63	0.03
18	W10	283	550	4.70	5.57	0.22	2.17	0.05
19	W11	288	550	2.46	5.47	0.27	1.86	0.14
20	W12	262	557	5.21	4.21	0.08	1.20	<0.007
21	W21	288	500	5.77	3.44	0.50	0.99	0.06
22	W22	289	394	1.00	1.44	0.36	1.04	0.15
23	W23	290	528	2.86	1.82	0.45	1.28	0.07
24	W24	288	485	4.70	4.05	0.48	1.60	0.12
25	W25	284	525	1.09	4.02	0.57	2.18	0.10
26	W26	285	502	3.32	5.24	0.32	1.39	0.04
27	W27	100	575	2.59	0.91	0.25	0.91	0.02
28	W28A	289	503	3.60	4.44	0.08	1.08	0.17
29	W29	288	535	3.70	5.18	0.27	1.40	0.10
30	W30	291	515	2.66	2.64	0.12	0.67	0.04
31	W31	288	560	3.74	2.39	0.24	1.19	0.03
32	W32	289	530	0.30	0.63	0.45	0.51	0.03
33	W33	290	502	0.46	1.36	0.07	0.35	0.05
34	W34	288	520	2.48	3.23	0.15	0.96	0.02
35	W35	288	553	0.65	1.60	0.04	0.17	0.02
36	W36	292	550	3.24	3.49	0.24	1.14	<0.007
37	W37	287	510	1.09	1.94	0.35	1.48	0.14

(*continued*)

Table 2 | continued

				Gross α (Bq/l)	Gross β (Bq/l)	^{226}Ra (Bq/l)	^{228}Ra (Bq/l)	^{210}Pb (Bq/l)
				Estimated uncertainty (Supplementary Table S2)				
	Well name	**Operating flow rate (m^3/hr)**	**Total well depth (m)**	5.8%	7.94%	9.39%	16.0%	5.60%
38	W38	289	500	2.31	4.16	0.37	1.70	0.14
39	W39	291	550	0.50	3.63	0.40	0.78	0.10
40	W40A	290	501	1.96	2.55	0.34	1.09	0.10
41	W41	287	478	2.91	5.14	0.24	1.47	0.09
42	W42	288	502	2.23	5.11	0.17	0.91	0.03
43	W43	288	500	2.47	6.28	0.60	1.62	0.02
44	W44	291	500	3.05	2.40	0.14	0.64	0.05
45	W45A	289	500	3.90	4.93	0.36	1.39	0.15
46	W46	260	553	1.42	1.94	0.11	0.64	0.02
47	W47A	265	526	2.31	3.21	0.33	1.39	0.02
48	W48	266	501	3.21	4.80	0.29	1.44	0.04
49	W49A	265	575	4.05	3.33	0.42	1.38	0.14
50	W50	265	550	3.12	3.13	0.29	1.20	0.09
51	W51	288	560	2.14	<0.28	0.50	0.09	0.20
52	W52	285	600	4.03	2.11	0.38	1.06	0.19
53	W53	285	575	2.92	2.93	0.37	1.32	0.37
54	W54	120	555	2.28	2.78	0.43	1.39	0.02
55	W55	190	560	1.72	2.95	0.65	1.20	0.01
	Detection limit	NA	NA	0.11	0.28	0.02	0.08	0.007
	Exceeding guideline	NA	NA	52	52	0	40	0
	Samples <detection limit	NA	NA	0	1	0	0	2
	Average	273	530	2.49	3.36	0.37	1.35	0.08
	Minimum	100	394	0.30	<0.28	0.04	0.09	<0.007
	Maximum	292	600	5.77	6.46	0.92	3.06	0.37
	Interquartile range	271–289	502–552	1.47–3.22	2.38–4.53	0.24–0.50	0.98–1.61	0.03–0.12

commissioning, and then monitored on a systematic basis for two years. To ensure the collection of representative groundwater samples, well water was systematically collected following purging of the well for at least three well volumes. Each unfiltered sample (23 litres with typically <2 mg/l suspended solids) was used to provide three subsamples: 8 litres for ^{228}Ra, 1 litre for ^{226} Ra, 1 litre for ^{210}Pb analysis and 1 litre for gross alpha and gross beta analysis. The remaining volume was retained to facilitate repeat analysis if required.

Samples for ^{228}Ra, ^{226}Ra and ^{210}Pb analysis were collected in virgin acid-washed polyethylene containers and acidified to a pH of <2 in the laboratory using 70% HNO_3 (Fluka >69% Grade). Samples for gross alpha and gross beta analysis were collected in virgin, acid-washed polyethylene or glass bottles and acidified to a pH of <2 in the laboratory using 37% HCl (Analar Normapur). Each sample was allowed to stand for at least 24 hours prior to chemical analysis to ensure that all acid-soluble substances entered solution.

After sampling of the well field had been completed, and water supply from the Ram aquifer system to Amman commenced, additional sampling started to allow the systematic determination of ^{226}Ra, ^{228}Ra and ^{210}Pb in the supply infrastructure and supplied households. Households in Amman typically receive pumped water on rotation on a three-in-seven day basis. Samples were collected only from distribution systems in areas which were being supplied with pumped water at that time. A similar sample collection and preservation routine was employed to that used during preliminary investigations of the well field.

Analytical methods

All analysis was undertaken at the joint Isotope Laboratory of the WAJ/MWI. This laboratory is accredited to ISO-17025:2005 and is recognized as a centre of excellence in the region for stable and radiological isotope analysis by the International Atomic Energy Agency (IAEA). The laboratory has been undertaking stable and radiogenic isotope analysis since the late 1980s, and undertakes annual proficiency testing among accredited national and international laboratories for radionuclides in a potable water matrix. Inter-laboratory proficiency testing confirms that the laboratory performance is good in terms of precision and accuracy (Supplementary Table S1). These data and analytical performance data (Supplementary Table S2) indicate that the methods used for the routine determination of the radioactive substances outlined in this report are fit for purpose and compliant with the most recent Jordanian drinking water standards (JS 2008).

Determination of gross alpha and gross beta activity

Gross alpha and gross beta analysis were performed via evaporative enrichment and liquid scintillation counting (LSC) using a Canberra Packard 3100TR liquid scintillation analyser equipped with alpha discriminator (pulse decay analysis). This methodology was developed in house, and has been validated for the determination of gross alpha and beta radioactivity by laboratory quality control schemes and accredited to ISO 17025:2005 in the WAJ/MWI laboratories. The quoted detection limits (0.11 Bq/l and 0.28 Bq/l, respectively) and combined uncertainty for these methodologies (5.80% and 7.94%, respectively) are given in Supplementary Table S2.

Whilst this method of analysis is gaining increasing recognition for the determination of gross alpha and beta activity in high total dissolved solids (TDS) waters (Sanchez-Cabeza & Pujol 1995; Lopes *et al.* 2010), it is acknowledged that this methodology tends to overestimate reported levels in comparison to techniques based on the more traditional evaporation and gas proportional counting. As a consequence, care must be used when comparing gross alpha and beta activities determined by different analytical methodologies (Jobbagy *et al.* 2010). In the Middle East, where the majority of waters are high TDS, and the radioactivity present predominantly due to natural series radionuclides, the method's overestimation of activity and high precision is considered to produce reproducible, conservative data on which to (a) trigger further assessments of radiological quality and (b) establish the success of water quality management.

Determination of ^{228}Ra

An 8-litre acidified sample was evaporated to a final volume of 1 litre. The residue was then placed in a high resolution gamma spectrometer (Canberra Low Level High Purity Germanium BE 5030 detector with 0.3 mm carbon window). This spectrometer has an efficiency of 50% and high resolution FWHM (full width at half maximum) of 2.2 at 1,332 keV. The methodology relies on measuring the emission of ^{228}Ra through ^{228}AC at 911 keV. This method provides a low detection limit (0.08 Bq/l) and is validated and accredited to ISO 17025:2005 in the WAJ/MWI laboratories for the determination of ^{228}Ra in drinking water with a combined uncertainty of 16%.

Determination of ^{226}Ra

Three hundred and fifty millilitres of sample was evaporated at 80 °C to reduce the volume to about 10 ml and then quantitatively transferred to the radon bubbler, where the final sample volume was 30 ml, and the bubbler closed and stored for 1 month to allow equilibration with ingrowing ^{222}Rn. The activity of ^{222}Rn was then determined using a RA1005 Radon Degassing Unit and Lucas cell. This method is modified from *Standard Methods* 20th edition 7500 Ra (A&C) and has been validated and accredited to ISO 17025:2005 in the WAJ/MWI laboratories for the determination of ^{226}Ra in drinking water. The method gave a detection limit of 0.02 Bq/l with a combined uncertainty of 9.4%.

Determination of ^{210}Pb

^{210}Pb was determined using the methodology described by Eichrom Technologies, Inc. (OTW01 Rev. 1.8) modified from *Standard Methods* 20th edition 7500 Ra (A&C) and has been validated and ISO accredited. The purified Pb fraction was collected after allowing ^{210}Bi to ingrow, and the activity of the ingrown isotope was determined using a Quantulus 1220 LSC. This method provided a detection limit of 0.007 Bq/l with an uncertainty of 5.6%.

Quantification of detection limits and methodological uncertainties

Performance criteria for the analytical methodologies employed in this work are given in the above paragraphs and summarized in Supplementary Table S2. These data demonstrate that analytical methodologies employed by WAJ/MWI for individual radionuclides are fit for purpose (i.e. the analytical detection limit is more than a factor of ten below the guidance values).

The analytical detection limits for gross alpha and gross beta are less fit for purpose, being only a factor of 4–5 below the established reference levels for these measurements (JS 2001, 2008; WHO 2004, 2011). Whilst this is not ideal, the methodological difficulties in measuring low levels of gross alpha and gross beta in groundwater are internationally acknowledged.

Assessment of data in relation to drinking water standards

The guidelines for assessing hazards posed by the presence of radionuclides in drinking water adopted by most countries including Jordan are derived from methodologies and practices outlined in the WHO guidelines for drinking water quality (WHO 1993, 2004, 2011). These in turn rely on the International Commission on Radiological Protection (ICRP) and IAEA basic safety standards recommendations (ICRP 2008; IAEA 1996, 2014), with differences in their approaches to calculation or assignment of an action value or maximum permissible dose for local enforcement. This approach allows for a strategy to be developed for reducing exposures via drinking water within the context of overall exposures to naturally occurring radioactive substances from within the workplace, food chain and local environment of the respective country and/or exposed population.

In addition, within arid environments, whilst the protection of public health always remains of paramount importance, it is also important that the costs and benefits of the remediation and/or intervention action be justified against the wider benefits to public health that result from having a reliable supply of domestic water. As a consequence, local conditions, i.e. scarce water resources, overall exposure to radiation from the different sources and the type of radiation were all taken into account during the development of the fifth edition of the Jordanian Drinking Water Standard (JS 2008) which sets a reference radiological limit (RRL) based on an effective committed dose of 0.5 mSv/y and an action limit (AL) of 1.0 mSv/y. These standards are similar in terms of maximum permitted dose to those developed in Australia which, like Jordan, is highly dependent on fossil groundwater for drinking purposes and as a result has had to balance the potential health impacts of radioactivity in drinking water sources against the need for drinking water (ADWG 2011). Both the WHO (WHO 2011) and Jordanian standards for drinking water (JS 2008) exclude any contributions to the annual radiological effective dose (AED) from ingestion of naturally occurring ^{40}K, which is homo-statically regulated in the human body, and inhalation and ingestion of ^{222}Rn, which is considered separately.

According to the WHO and ICRP, background radiation exposures vary widely across the Earth from an average of about 2.6 mSv/y in the UK (NRPB 1998) to a maximum in the order of 260 mSv/y in Iran, without any detectable increased health risks from population studies (Ghiassi-nejad *et al.* 2002). In addition to background sources of radioactivity, significant additional exposure to radioactivity routinely result from medical exposures, especially due to the increasing of computed tomography scans, and typical doses derived from these sources in the USA exceed 3 mSv/y (Brenner & Hall 2007). According to figures from the Jordanian Nuclear Regulatory Commission, the annual background radiation exposure in Jordan is 1.8 mSv, excluding the city of Aqaba. This is almost four times the national AL for radioactivity as outlined in JS (2008).

Estimation of radiological dose from drinking water

Methodologies for the calculation of an individual's annual radiological effective committed dose from the consumption of naturally occurring and man-made radionuclides via the drinking water pathway, and/or the concentration of a specific radionuclide in drinking water that would result in a dose that exceeds a specific individual dose criterion, are laid out in the WHO and Jordanian standards for drinking water quality (WHO 1993, 2004, 2011). In these calculations (Supplementary Table S4) Jordanian regulations (JS 2008) require the use of an adult drinking water consumption rate of 730 l/y, an individual dose criterion of 0.5 mSv/y and the use of dose coefficients listed in Supplementary Table S3 (as derived from WHO 1993, 2008, 2011). When more than one of these radionuclides are present, the resulting AED represents a summation of AED equivalents from each of the radioelements present.

Based on data from previous studies of groundwater from the Ram aquifer, radionuclides that are the highest contributors to radiological dose through the consumption of Disi water directly at the well head are ^{228}Ra, ^{226}Ra and ^{210}Pb.

The dose coefficients used (Supplementary Table S3) are those for an adult, as both the 2008 and 2011 WHO drinking water standards state that there are insufficient data to allow for the calculation of an effective committed dose for age groups such as young adults and children (WHO 2008, 2011). However, both this work and calculations made by others (Dababneh pers. comm. 2014; Vengosh *et al.* 2014) indicate there is a need for further research and studies to better understand the radiological dose received by non-adults and its potential effects over the longer term.

RESULTS

The results from the initial pre-commissioning survey of gross alpha, gross beta, ^{226}Ra, ^{228}Ra and ^{210}Pb in waters from the Disi and Mudawara well field that supplies water to the DWCP are presented and summarized in Table 2. These results indicate generally elevated gross alpha and beta activities in all the 55 wells sampled, and generally agree with previous WAJ/MWI investigations on a more limited subset of wells (Table 1). Amongst the individual determined isotopes, ^{228}Ra accounts for the greatest proportion of total activity in the individual wells, and by inference the collective water from the Disi basin that is supplied, via the conveyance system, to Amman. For the purposes of statistical calculations, activities corresponding to the isotopes' detection limit have been substituted where the result was below the analytical detection limit. The impact of this conservative assumption (Helsel 2005) on the data set as a whole is small, given that this rule had to be used only three times out of 324 individual analyses.

Since this initial assessment performed in early 2013, a further round of sampling and radiochemical analysis has been performed on samples from all operating wells within the well field, and a second additional round of analysis is almost complete. Results from these further analyses, summarized in Table 3 and displayed graphically in Supplementary Figures S4 and S5, respectively, confirm the relative importance of ^{228}Ra established from initial survey data (Table 2). In the second sampling round, the number of wells exceeding the guidance levels for ^{228}Ra decreased from 40 to 31. Whilst the average and maximum activities of ^{226}Ra and ^{228}Ra have remained constant within analytical uncertainty, the interquartile range has widened.

Yearly analysis of blending waters from Zara-Ma'en and Zai treatment plants from August 2012 through January 2014 for gross alpha, gross beta, ^{226}Ra and ^{228}R were all below the respective methods' analytical detection limits (Supplementary Table S2; all Supplementary Figures and Tables are available with the online version of this paper).

DISCUSSION

Pre-commissioning data for the Disi and Mudawara well field (Tables 2 and 3) show that almost all the 55 wells exceed the screening values for gross alpha and gross beta activities specified in the Jordanian Drinking Water Standard (JS 2008). Fifty-two wells exceeded the gross alpha standard and 52 wells exceeded the gross beta standard. This is clearly demonstrated in Figure 2, where gross alpha and gross beta activity for each individual well (Table 2) are plotted against each other with error bars representing combined analytical uncertainties of these measurements. The frequency

Table 3 | Summarized data for well field sampling rounds undertaken following 0, 6 and 12 months' abstraction from the well field and calculated radiological dose assuming water consumption at individual boreholes

Measured radiological activity (Bq/l)

	0 months' abstraction		**6 months' abstraction**		**12 months' abstraction**	
	55 out of 56 wells sampled		**50 out of 56 wells sampled**		**54 out of 56 wells sampled**	
Isotope	^{226}Ra	^{228}Ra	^{226}Ra	^{228}Ra	^{226}Ra	^{228}Ra
Detection limit	0.02	0.08	0.02	0.08	0.02	0.08
Number exceeding guideline	0	40	0	33	0	37
Samples <detection limit	0	0	0	0	0	0
Average	0.37	1.35	0.38	1.29	0.40	1.31
Minimum	0.04	0.09	0.06	0.18	0.10	0.24
Maximum	0.92	3.06	0.85	2.44	0.92	2.72
Interquartile range	0.24–0.50	0.98–1.61	0.19–0.56	0.78–1.75	0.20–0.54	0.97–1.73
Average calculated radiological dose (mSv/y) based on measurements from individual boreholes						
	Minimum	Average	Maximum	25th percentile	25th percentile	75th percentile
^{226}Ra 0 months	0.01	0.08	0.19	0.05	0.10	0.08
^{228}Ra 0 months	0.05	0.68	1.54	0.49	0.81	0.68
^{210}Pb 0 months	<0.04	0.04	0.19	<0.04	0.06	0.04
Total 0 months	0.06	0.80	1.92	0.56	0.97	0.80
^{226}Ra 6 months	0.01	0.08	0.17	0.04	0.11	0.08
^{228}Ra 6 months	0.09	0.65	1.23	0.39	0.88	0.65
^{210}Pb 6 months[a]	<0.04	0.04	0.19	<0.02	0.06	0.04
Total 6 months	0.10	0.77	1.59	0.45	1.06	0.77
^{226}Ra 12 months	0.02	0.08	0.19	<0.04	0.11	0.08
^{228}Ra 12 months	0.12	0.66	1.37	0.49	0.87	0.66
^{210}Pb 12 months[a]	<0.04	0.04	0.19	0.04	0.06	0.04
Total 12 months	0.10	0.78	1.75	0.52	1.02	0.78
Overall average total	0.09	0.78	1.75	0.51	1.02	0.78

[a] ^{210}Pb not determined in 6 and 12 monthly rounds. Data for initial round therefore supplemented in calculation of total dose for 6 and 12 month sampling rounds.

distributions of gross alpha and gross beta activity are broadly similar, and consistent with normally distributed data sets (Supplementary Figure S6; all Supplementary Figures and Tables are available with the online version of this paper). A discernible break into two identifiable distributions appears to occur when gross alpha activities lie below 1 Bq/l (wells W32, W33, W35, W39, P1, P5 and P6). This break is not observed within the gross beta data set.

The downhole natural gamma ray logging of selected boreholes (Supplementary Figure S3) shows no direct correlation between observed activities and well depth (Table 2), although limited results from some wells in the approximate vicinity of the geologic faults indicate correlations may exist. A degree of correlation is also observable between levels of dissolved radioelement content and the type of formations transected by an individual borehole.

Measurements of activity in the second and third rounds of sampling broadly confirm the spatial distribution of radioactivity seen in the initial survey of the well field. Although the mean output concentrations of ^{226}Ra and ^{228}Ra from the well field remain approximately constant on a well-by-well basis, it can be seen that some wells are increasing in

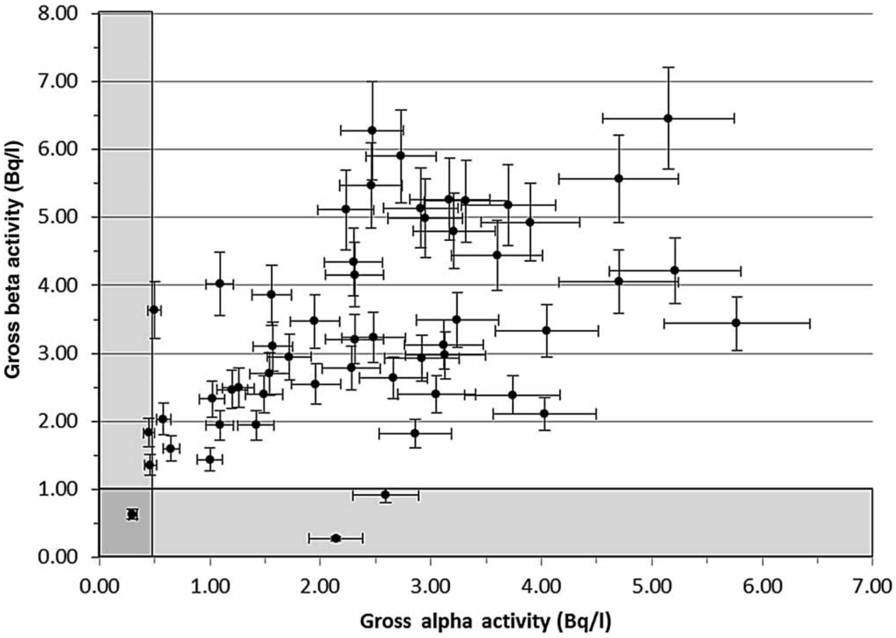

Figure 2 | Plot of gross alpha and gross beta activity for the 54 well water samples. Shaded areas represent Jordanian action levels for gross alpha and gross beta activity.

^{228}Ra and ^{226}Ra whilst others are decreasing (Supplementary Figures S4 and S5). Further sampling rounds are planned to monitor the radiological characteristics of each well, thereby allowing comparison of a total of four sampling rounds over two years of continuous abstraction from the well field. After the initial two years of monitoring, well head radionuclide concentrations will continue to be monitored on a yearly basis over the lifetime of the project.

Estimation of effective dose at the well head

Despite the fact that water from the Ram aquifer is typically being consumed >300 km from the well field (equating to a transit time of between 2 and 3 days) and subjected to mixing with other more local water sources during blending, it was considered prudent, based on previous studies (e.g. Vengosh *et al.* 2009; Mott MacDonald 2009) to compare the derived AED at the well head of each of the boreholes in the well field as part of the commissioning process.

Firstly, the individual activities of contributing radionuclides (^{226}Ra, ^{228}Ra, and ^{210}Pb) were compared against action levels (Supplementary Table S3) for these individual radionuclides (i.e. conservatively assuming that the water from each well was consumed by an adult at the well head). The results of this comparison for pre-commissioning well field data are shown in Supplementary Figure S7, from which it can be deduced that individual guidance levels are only exceeded in the case of ^{228}Ra, where the guidance level lies at the lower quartile (25th percentile) of the measurements listed in Table 2.

Secondly, in line with the Jordanian standard and WHO guidelines, the AED was calculated individually for ^{226}Ra, ^{228}Ra and ^{210}Pb as set out in 'Estimation of radiological dose from drinking water section' (see Methodology) and Supplementary Table S4. In undertaking these calculations, no allowance has been made for the presence of ^{226}Ra and ^{228}Ra daughter products as:

- their respective contribution to the dose was low compared to that of their parents (^{226}Ra and ^{228}Ra); furthermore gaseous daughters like ^{222}Rn are excluded from the calculation of the AED (JS 2008; WHO 2011);
- due to a combination of their chemical and radiological properties, the presence of these daughter products had only been detected at very low levels in this and previous unpublished studies on groundwater from the Disi and Mudawara well fields (^{210}Pb and ^{210}Po).

The results of these calculations are summarized in Table 3 and Supplementary Figure S8 with the total calculated total AED for all these radionuclides. The results shown re-emphasize the dominant contribution made by ^{228}Ra to the total AED of well waters from this aquifer. On a sample-by-sample basis, the contribution of radioactivity from ^{228}Ra to the total AED exceeds 70% with the exception of two samples (W3 and W51) where the contributions from ^{228}Ra to the total estimated dose were significantly lower (28% and 50%, respectively).

Comparison of these calculated total AED values (Table 3), derived from data in Table 2, to an RRL of 0.5 mSv/y indicate on an individual basis that only 9 of the 55 sampled wells meet Jordanian water quality guidelines if they were to be consumed at source for a full year. The highest 'at source' AED in the pre-commissioning data set was estimated to be 1.70 mSv/y on the basis of ^{228}Ra, ^{226}Ra and ^{210}Pb, whilst the average total dose for all individual wells was 0.82 mSv/y. The calculated radiological dose from the combined discharge of the well field calculated by weighting the individual well head doses by the potential contribution of each well to the total water yield of the well field is 0.80 mSv/y. This is close to the mean and median of the individual wells (0.81 mSv/y, Table 3).

The measured total dose of the combined discharge during the full period of the operation phase (0–12 months is 0.78 mSv/y). However, whilst the total production potential of the well field is 132 million m^3/y only 100 million m^3/y is currently contracted to be delivered to WAJ/MWI. Consequently, if total well production is limited to 100 million m^3/y and wells whose waters contain the highest concentrations of radioactivity were to be excluded from the abstraction process then the estimated effective dose from the combined well field output would be lower (calculated to be approximately 0.64 mSv/y). This option is being considered by WAJ/MWI and the DWCP Company. During the operational phases of the project, the average calculated radiological dose assuming consumption of water at the entry point of each of the mixing reservoirs was 0.72 ± 0.05 mSv/y (Table 4). Whilst this average is slightly lower than the theoretical dose calculated from the contribution from individual wells (Table 3), data from the individual wells and entry into the mixing reservoirs lie within the measured monthly range (±0.05 mSv/y (1 Sigma)).

When compared to the Jordanian standard, the calculated AEDs for individual wells, and the combined flow from the well field clearly demonstrate that such waters, if they were to be supplied directly without dilution (blending) would result in consumers being exposed to AEDs exceeding the Jordanian RRL of 0.5 mSv/y. However, even at the full abstraction rate combined water from the well field (based on weighting the wells' AED according to each wells' yield) would be below the Jordanian standards AL of 1 mSv/y. Additionally none of the calculated doses exceeded the estimated radiological dose from all natural sources in Jordan (1.8 mSv/y, excluding the city of Aqaba), although the average estimated dose is approximately 45% of this figure if all wells are pumped, or approximately 36% if pumping from the well field is optimized to minimize the effective dose from abstracted water.

On a well-by-well basis, approximately 75% of the sampled waters were below the Australian AED standard for drinking water (1.0 mSv/y) and ICRP recommendations for a single consumed commodity of 1.0 mSv/y (ADWS 2011; IAEA 1996).

As a direct result of the initial findings and ongoing confirmatory work, WAJ/MWI and the DWCP Company investigated a range of intervention measures and treatment options to reduce the potential radioactive dose received by Jordanian consumers at the actual point of consumption to as low a level as possible, below the Jordanian action level of 0.5 mSv. At the same time, a sampling and analysis programme was established to:

- monitor any changes of radioactivity levels in the Disi and Mudawara well field (the preliminary results for this program to date have been discussed above);
- inform and test the effectiveness of intervention and treatment options.

The development of intervention options and associated activities are discussed in the following sections.

Intervention and treatment options

Initial intervention and treatment options began to be developed during 2003, prompted by preliminary surveys of water quality undertaken by MWI/WAJ. The options were focused on a variety of potential 'passive' and 'active' remediation options aimed at reducing the worst case scenario dose of approximately 0.8 mSv/y. These options were reviewed again following international concerns in respect of the

Table 4 | Blending ratios and calculated AED dose for the Dabouk and Abu Alanda networks

Month	Zai water amount (m^3/month)	Disi water amount to Dabouk (m^3/month)	Blending ratio (Zai/Disi)	AED[a] Disi water (mSv/y)	AED Dabouk network (mSv/y)
Jul-13	4,500,543	2,618,167	1.72	0.82	0.34
Aug-13	6,262,195	4,605,195	1.36	0.81	0.34
Sep-13	5,703,455	4,447,934	1.28	0.65	0.27
Oct-13	5,161,015	4,446,410	1.16	0.76	0.32
Nov-13	3,472,324	4,732,380	0.73	0.70	0.40
Dec-13	3,593,514	4,657,914	0.77	0.73	0.38
Jan-14	3,634,844	5,283,963	0.69	0.73	0.50
Feb-14	3,252,400	4,950,419	0.66	0.68	0.43
Mar-14	3,447,677	5,768,280	0.60	0.73	0.43
Apr-14	3,926,622	5,509,420	0.71	0.69	0.49
May-14	4,215,636	5,804,439	0.73	0.72	0.40
Jun-14	4,045,449	5,626,131	0.72	0.62	0.40
Jul-14	5,614,981	5,924,196	0.95	0.67	0.36
Total	56,830,655	64,374,848	–	–	-
Average	–	–	0.88	0.72	0.39

Abu Alanda

Month	Zara-Ma'en amount m^3/month	Disi water amount to Abu Alanda	Blending ratio (Zara/Disi) m^3/month	AED[a] Disi water (mSv/y)	AED Abu Alanda network (mSv/y)
Jul-13	Not in Operation				
Aug-13	398,360	97,022	4.11	0.81	nm
Sep-13	1,116,000	625,854	1.78	0.65	0.34
Oct-13	2,232,000	685,397	3.26	0.76	nm
Nov-13	2,160,000	1,714,467	1.26	0.70	0.43
Dec-13	2,232,000	2,309,966	0.97	0.73	0.42
Jan-14	2,631,599	2,874,795	0.92	0.73	0.50
Feb-14	2,107,703	2,734,577	0.77	0.68	0.37
Mar-14	1,456,433	3,216,956	0.45	0.73	0.73
Apr-14	2,321,351	2,558,113	0.91	0.69	0.36
May-14	2,230,767	2,623,942	0.85	0.72	0.37
Jun-14	2,068,924	2,601,492	0.80	0.62	nm
Jul-14	2,394,167	2,622,680	0.91	0.67	0.41
Total	20,955,137	22,042,581	0.95	0.72	0.44
			Average	Average	Average

[a] Data based on measurement of radioactivity present at the inflow to each mixing reservoir.

radiological quality of water drawn from the Ram aquifer system (Mott MacDonald 2009; Vengosh *et al.* 2009; Schubert *et al.* 2011). The underlying principle used in the selection of remedial measures was that any option lowering radiation exposure should (a) do more good than harm in terms of individual exposures to naturally occurring radionuclides (i.e. achieving a net benefit and the ALARA (as low as reasonably achievable) principle (IAEA 1996)) and (b) should be economically and environmentally sustainable (USEPA 2005; WHO 2011).

After carefully considering a number of active treatment options for treating the 100 million m^3/y abstraction from the well field, such as reverse osmosis, nano-filtration and lime softening, via environmental and cost–benefit analysis, it was decided that the most practicable and sustainable option for Jordan would be to blend waters from the Disi and Mudawara well field with other groundwater, and preferably surface water resources (when and where available).

This judgment was made on the basis of the following:

- The availability of a sufficient quantity of water, with a low radionuclide content, for blending.
- The need to improve the chemical and biological quality of water currently supplied to Amman.
- Benefits to the population where the Jordanian water quality standards (JS 2008) can be achieved with limited additional cost, thereby allowing resources to be better focused.
- Benefits to the environment, as there is no generated waste that requires national and local waste management strategies and guidelines.
- Cost effectiveness in terms of the cost of a treatment facility and the corresponding cost of waste handling, transport and disposal.
- Long-term flexibility, allowing for future treatment and water conveyance planning to further optimize the use of water from the Disi and Mudawara well field.

The case for using a blending approach was further strengthened by the presence of existing infrastructure such as the storage and mixing facilities at Dabouk and Abu Alanda. In these facilities (lying on the outskirts of Amman), it is feasible to mix transported water from the Disi and Mudawara well field with water derived from the Zai water treatment plant (annual yield 85–90 million m^3/y) and Zara Ma'en water supply system (annual yield 40–45 million m^3/y). As stated previously, radiochemical analysis of these sources typically showed activities of ^{226}Ra, ^{228}Ra and ^{210}Pb to be below the methodological detection limits (Supplementary Table S2) and indicate that both of these waters, which are principally derived from surface water bodies, have an AED of <0.02 mSv/y. On this basis,

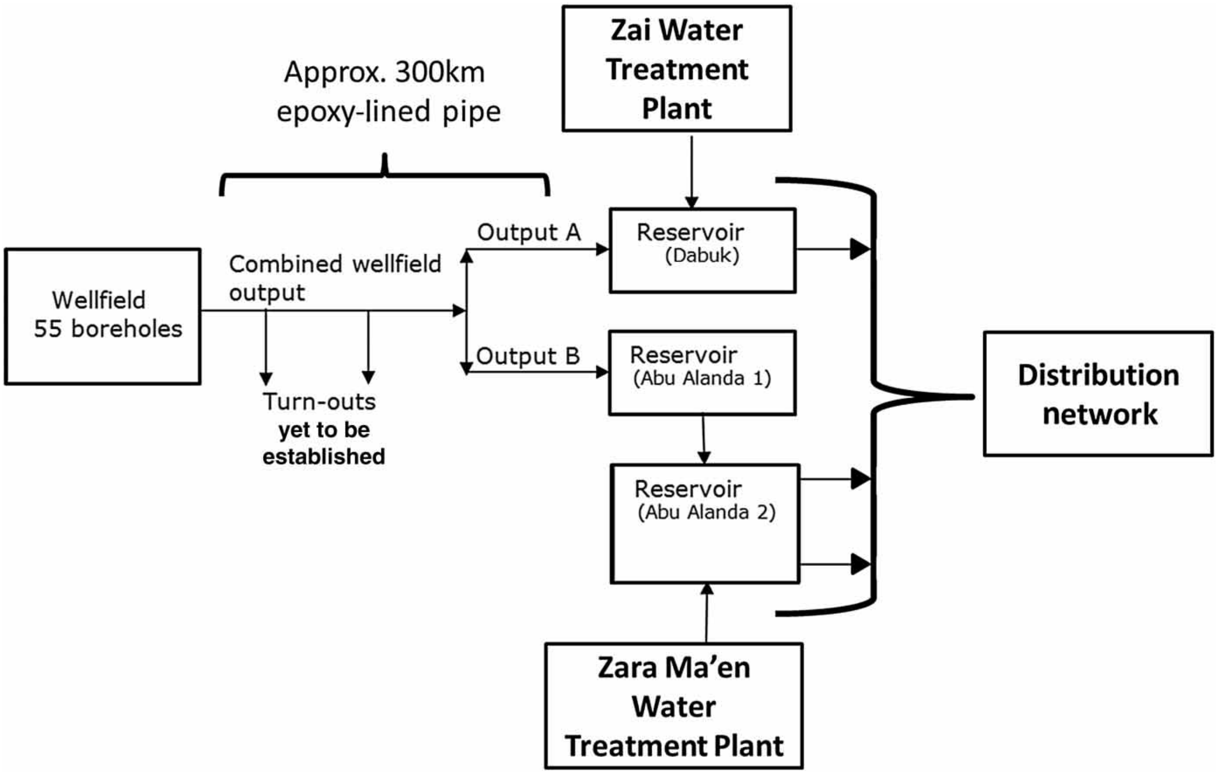

Figure 3 | Simplified schematic diagram of the well field and associated infrastructure put in place to allow blending on the outskirts of Amman.

WAJ/MWI planned and commissioned a system for blending Disi and Mudawara well field water with water from the Zai and Zara Ma'en plants. The system put in place for undertaking this dilution process is shown schematically in Figure 3, and a partial delivery arrangement with DWCP started supply to Amman in July 2013.

On the basis of available blending water and the concentration of radioactivity in water from the Disi and Mudawara well field, a blending ratio of 1 part Disi to 1 part Zara/Zai was theoretically possible, resulting in a 50% decrease in the concentration of radioactivity entering the water supply system. However, as water demand and supply vary seasonally, it was accepted that this theoretical mixing ratio could not be absolutely guaranteed, especially given that both Zai and Zara Ma'en treatment plants are subject to disruption during periodic flooding and severe rain events. Table 4 show the actual mixing ratios obtained since the system was commissioned in July 2013 along with calculated AED (mSv/y) associated with measurements of ^{228}Ra and ^{226}Ra before and after blending (Figures 4 and 5). The calculated AED in the customers' network (i.e. the point at which water enters the consumers' premises) corresponds to an annual average of 0.39 mSv/y in the Dabouk Reservoir network and 0.44 mSv/y in the Abu Alanda Reservoir network.

Over the year, both systems have managed to reduce the potential effective dose received from drinking water by approximately 40%, a reduction that achieved full compliance with the requirements of the Jordanian Drinking Water Standard for radiological parameters (RLL 0.5 mSv/y).

Whilst WAJ/MWI are constrained by contract with DWCP to continue to monitor the well field on a systematic basis and blending on a monthly basis by the collection of

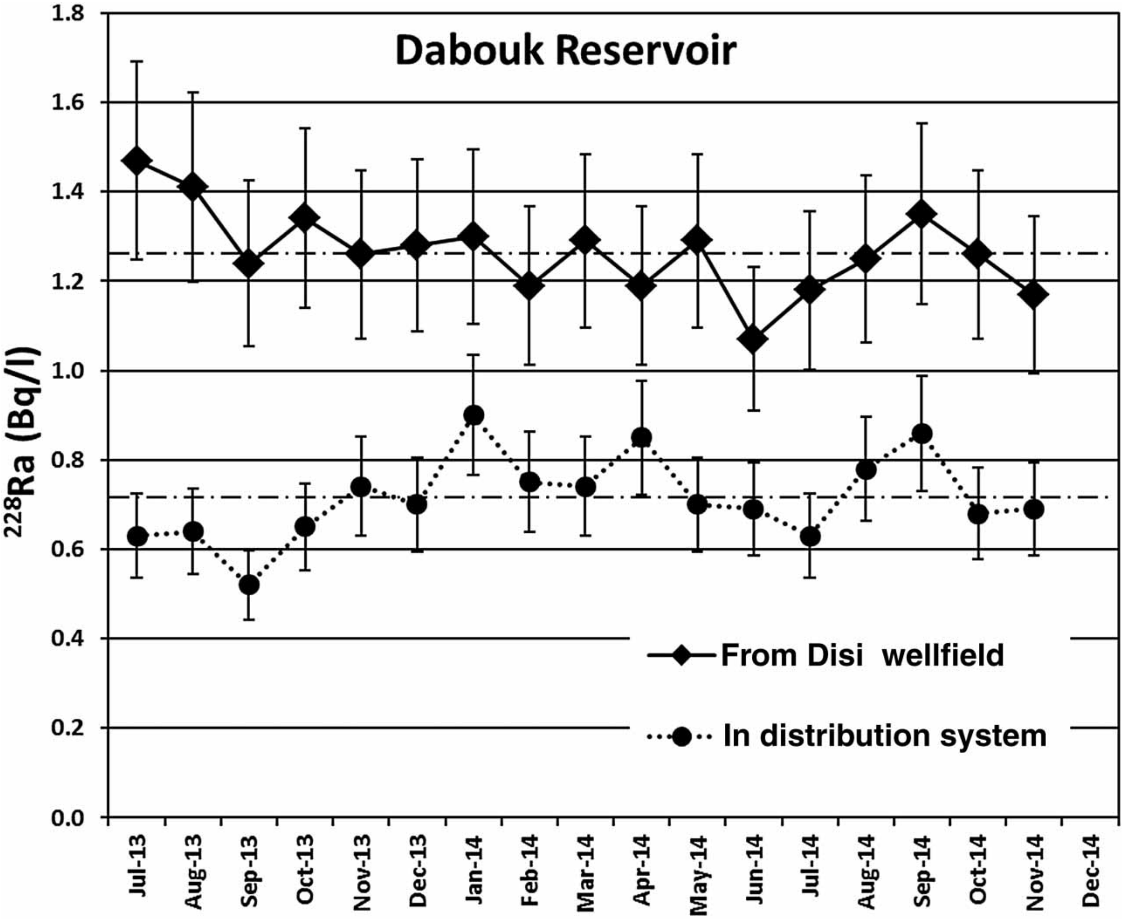

Figure 4 | Concentration of ^{228}Ra from the Disi well field and that entering the public distribution network via Dabouk.

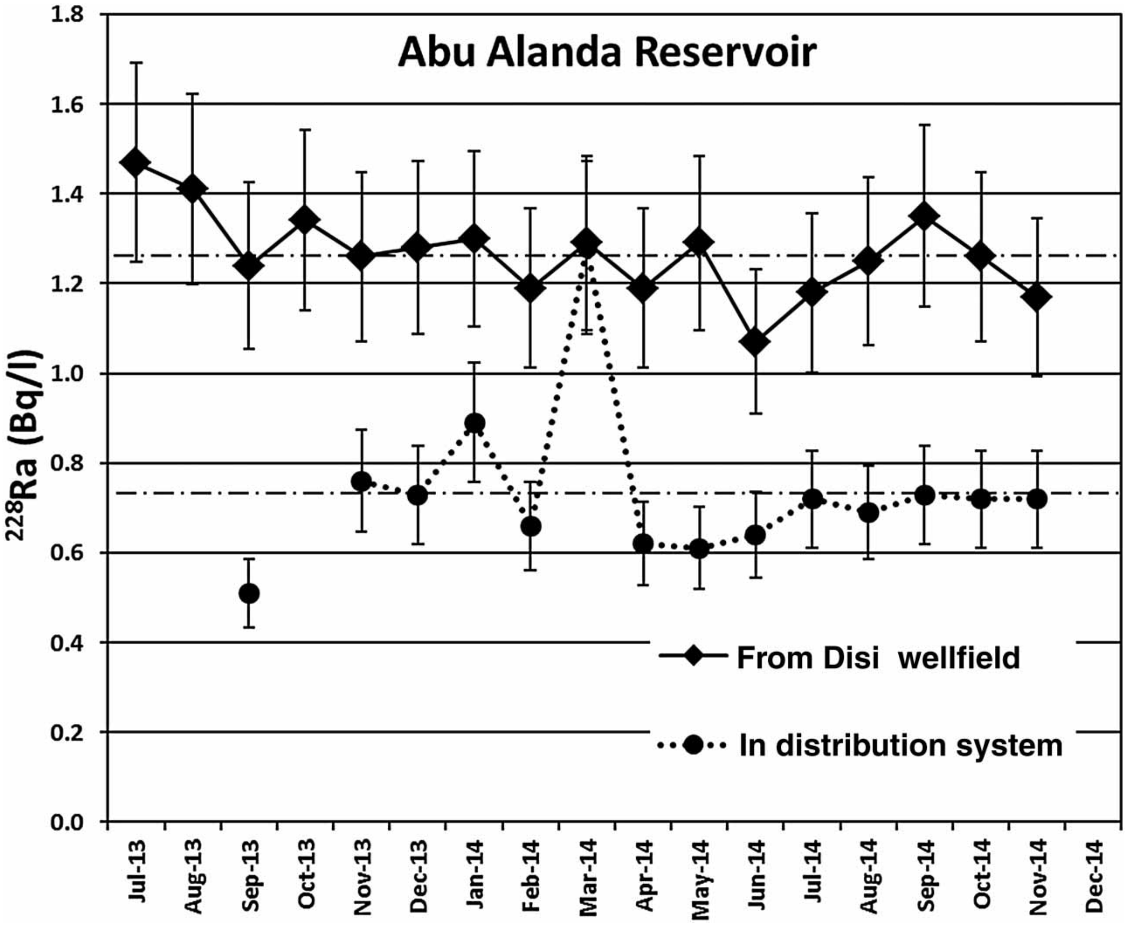

Figure 5 | Concentration of ^{228}Ra from the Disi well field and that entering the public distribution network via Abu Alanda.

single point samples, WAJ/MWI are investigating the possibility of employing a combination of continuous online monitoring and composite sampling to provide more reliable and timely information on levels of radioactivity entering the distribution system. It is hoped that this more timely information will lead to improved management of the abstraction and supply of Disi water to Amman.

Emerging issues and investigations

Recent publications (Vengosh *et al.* 2014) and international guidance (ICRP 2006; WHO 2004, 2011) highlight the need to consider lifetime exposure, and exposure to younger age groups, when evaluating impacts from radioactive substances in drinking water. However, whilst considering the feasibility of this approach, WHO (2011) cautions that 'Insufficient evidence was found to introduce separate guidance levels for different age groups. Although infants and children consume a lower mean volume of drinking-water, the age-dependent dose coefficients for children are higher than those for adults, accounting for higher uptake or metabolic rates. In the case of prolonged contamination of the water source, an assessment of doses to infants and children may be considered.'

In order to test these assumptions WAJ/MWI used:

- ICRP and USEPA data to provide bio-kinetic and effective dose conversion data for newborn, 1yr, 5yr, 10yr, 15yr and adults (USEPA 1999; ICRP 2013);
- data for water consumption within the same age groups from the USA (Ershow & Cantor 1989);
- an assumed average lifetime of 70 years (i.e. duration of exposure).

When combined with measured concentrations of ^{226}Ra and ^{228}Ra in the water distribution network, these data (Supplementary Table S5) allowed the cumulative effective dose over a 70-year lifetime to be calculated and for this to be compared against estimates based on industry recommended approaches (WHO 2011) and Jordanian standards (JS 2008) to be made. The results of these calculations (Table 5) indicate that the approach recommended in the 3rd and 4th editions of the WHO drinking water guidelines (WHO 2004, 2011) and used in local standards (JS 2008) is conservative in terms of estimating the cumulative dose received from drinking blended Disi water, although it could be argued that the difference between the age-group-related approach and the use of a constant adult dose conversion factor lies within the levels of uncertainty associated with the age group related data sets. Using either approach, results estimated levels of lifetime accrued dose that are around 25% of the estimated total lifetime cumulative dose from all radiation sources in Jordan (excluding Aqaba).

In line with the ALARA principle over the next two years, WAJ/MWI will continue to put in place measures with the aim of reducing concentrations of radioactivity (dominantly from ^{228}Ra) in the blended water output from Disi and other water sources in the Kingdom. Measures currently being considered include, but are not limited to, reducing:

- levels of radioactivity leaving the well field by prioritizing abstraction from wells with the lowest levels of ^{228}Ra and the drilling of new wells in areas proven to be lower in radionuclide content; and
- the quantity of local water low in radioactivity made available for blending along the extent of the national carrier allowed greater dilution ratios to be utilized on a more frequent basis.

Table 5 | Estimated cumulative lifetime dose (mSv) based on concentrations of ^{226}Ra and ^{228}Ra as measured in blended Disi water

Scenario	^{226}Ra (0.23 Bq/l) ^{228}Ra (0.76 Bq/l)
Constant water consumption and adult dose conversion factor (WHO 2011; JS 2008)	35 mSv
Age dependent water consumption and dose conversion factors (Supplementary Table S5) DCF and water consumption (Supplementary Table S5)	29 mSv
Lifetime dose at RRL (JS 2008)	35 mSv
Lifetime dose from background radiation in Jordan (1.8 mSv/y)	126 mSv

At the same time, WAJ/MWI are working with other bodies involved in setting national and international drinking water standards to better constrain dose estimates through developing a better national picture of water consumption amongst children and young adults, and to convey the basis behind their decisions to members of the public (i.e. improve risk communication).

CONCLUSIONS

Results of our work to date have indicated that the initial mean committed effective dose of each of the 55 wells due to natural radioactivity at the well head during the construction phase of the project was 0.80 mSv/y and reached 0.78 mSv/y during the subsequent operational phases. However, this is not the water directly consumed by the public.

The majority of the effective dose at source and following conveyance was identified as being due to the presence of ^{228}Ra, a member of the thorium decay chain. Radium-226 was also observed but did not constitute the major component in terms of effective dose. Uranium, thorium and other major members of their decay chain such as ^{210}Pb, ^{224}Ra and ^{210}Po were present at low concentrations, and as such did not contribute to >5% of the calculated effective dose.

Blending was identified as the most practicable option to reduce the potential radiological dose received by consumers by the relevant water and health authorities in Jordan after careful considerations of the costs and benefits of possible management options and actions. Theoretical calculations of the impact of mixing on the activities of ^{226}Ra, ^{228}Ra and ^{210}Pb in the distribution system and consumers' taps, and the estimated dose to consumers, indicated that the approach would allow the supply of tap water compliant with Jordanian standards (JS 2008).

Results from monthly sampling rounds undertaken by collecting water from consumers' dwellings whilst blending was in full-scale operation were 0.39 mSv/y in Dabouk Reservoir network and 0.44 mSv/y in Abu Alanda Reservoir network.

These data support the adoption of this approach and indicate that: (a) radionuclide levels reaching the consumer fully comply with Jordanian standards for water quality in respect of their radioactive constituents (i.e. result in an estimated yearly committed effective dose of <1 mSv/y); and (b) result in a lifetime accrued dose that is <25% of the estimated total accrued dose from all radiation sources in Jordan. Such doses whilst calculated for regulatory purposes would not be expected to produce an identifiable health detriment.

The health of water consumers is further protected by the Jordanian drinking water standards being derived from appropriately conservative assumptions and safety factors in relation to: estimated per capita water consumption; internationally agreed dose conversion factors as recommended by WHO and the IAEA; and the protective nature of radiological standards, which currently include the assumption of a linear no-threshold relationship between effective committed radiological dose and potential health detriment.

The WAJ/MWI is considering lowering the predicted effective dose present at the consumers' point of supply even further by optimization of the well field pumping regime to achieve 0.64 mSv/y as raw Disi water, i.e. attaining a potential reduction of 28% from the initial dose during construction phase.

Furthermore, WAJ/MWI envisages putting in place measures to maximize the amounts of water blending after the construction of the national water conveyor and the reallocation of the water supply along the extension of the conveyor from south to north.

In conclusion, WAJ/MWI and others in Jordan are aware of radioactivity in water from Disi and indeed many other waters from the country and its neighbours. In developing the Disi resource, they have put in place mitigation measures that allow this valuable groundwater resource to be exploited and at the same time meet the sometimes competing needs for both water quality and water quantity in relation to human health and environmental quality.

As is the case for all nationally strategic water resources, WAJ/MWI will continue to monitor the radioactivity present in the raw water and blended water as per the requirements of the national standards and pertaining water sector strategy.

ACKNOWLEDGEMENTS

The authors wish to thank the Secretary General of the Water Authority of Jordan (WAJ) and his staff, who worked tirelessly to monitor and deliver high quality water to Amman. Sincere thanks would also go to the CEO of Miyahuna Water Company and to his team for optimizing the blending regimes at the Disi raw water delivery points with water from Zai and Zara Ma'en sources. A special word of gratitude is due to AFD for their support in equipping the WAJ laboratory with state of the art analytical facilities for radioactive parameters in water and soil samples and to the DWCP lenders, project company and operators. The authors would also like to give special thanks and appreciation to Oliver Smith, who assisted in drafting the images included as figures in this paper.

REFERENCES

ADWG 2011 *Australian Drinking Water Guidelines 6 2011 Version 2.0 Updated December 2013*. National Health and Medical Research Council, Canberra, Australia.

Becker, M. 2012 Contaminated aquifers: Radioactive water threatens Middle East. *Der Spiegel International*, 5 November 2012.

Brenner, D. J. & Hall, E. J. 2007 Computed tomography – an increasing source of radiation exposure. *N. Eng. J. Med.* **35**, 2277–2284.

BRGM (Bureau de Recherches Geologiques et Minieres) 2008 Investigations for updating the groundwater mathematical model(s) of the Saq and overlying aquifers. Technical report prepared by BRGM on behalf of the Ministry of Water and Electricity, Water Resources Development Department, Kingdom of Saudi Arabia.

Buckle, D. J. E. 1993 *Borehole Geophysical Investigation and Hydraulic Parameter Determination of the Sandstone Aquifer System in the Southern Desert of Jordan*. Submitted in partial fulfilment of MSc in Hydrogeology at University College London, UK, September 1993.

Cothern, C. R. 1987 Development of regulations for radionuclides in drinking water. Radon, radium and other radioactivity in groundwater: *Hydrological Impact and Application to Indoor*

Airborne Contamination; Proceedings of NWWA Conference (Somerset, New Jersey), pp. 1–11.

Dababneh, S. 2014 Written statement provided to B. Smith and S. Kilani, 10 December.

El-Naser, H. K. 2009 Management of scarce water sources: a Middle Eastern experience. In: *International Series on Progress in Water Resources*. Vol. 14. WIT Press. Southampton, Boston.

Ershow, A. G. & Cantor, K. P. 1989 Total tap water and tap water intake in the United States: Population-Based Estimates of Quantities and Sources, Order No. 263-MD-810264, National Cancer Institute, Bethesda, MD.

Gedeon, R., Smith, B., Amro, H., Jawadeh, J. & Cook, J. M. 1994a Uranium rich mineralised groundwaters from Central Amman, Jordan. In: *Applications of Tracers in Arid Zone Hydrology*, E. M. Adar & C. Leibundgut (eds). IAHS Publication 232, IAHS Press, Wallingford, UK, pp. 171–182.

Gedeon, R., Smith, B., Amro, H., Jawadeh, J. & Kilani, S. 1994b Natural Radioisotopes in Groundwaters from the Amman-Zarka Basin Jordan, Hydrochemical and Regulatory Implications. In: *Applications of Tracers in Arid Zone Hydrology*, E. M. Adar & C. Leibundgut (eds). IAHS Publication 232, IAHS Press, Wallingford, UK, pp. 81–98.

Ghiassi-nejad, M., Mortazavi, S. M. J., Cameron, J. R., Niroomandrad, A. & Karam, P. A. 2002 Very high background radiation areas of Ramsar, Iran: preliminary biological studies. *Health Phys.* **82**, 87–93.

Helsel, D. R. 2005 *Non Detects and Data Analysis – Statistics for Censored Environmental Data*. John Wiley & Sons, New Jersey.

Humpal, D., El-Naser, H. K., Irani, K., Sitton, J., Renshaw, K. & Gleitsmann, B. 2012 *A Review of Water Policies in Jordan and Recommendations for Strategic Priorities* United States Agency for International Development.

IAEA (International Atomic Energy Agency) 1996 *International Basic Safety Standards for Protection Against Ionizing Radiation and for the Safety of Radiation Sources*. IAEA Safety Series No 115, IAEA, Vienna.

IAEA (International Atomic Energy Agency) 2014 *Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards. General Safety Requirements Part 3*. IAEA Safety Standards Series No. GSR Part 3, July 2014, IAEA Vienna.

ICRP (International Commission on Radiological Protection) 2006 Assessing Dose of the Representative Person for the Purpose of the Radiation Protection of the Public. *ICRP Publication 101a. Ann. ICRP*, **36** (3).

ICRP (International Commission on Radiological Protection) 2008 The 2007 recommendations of the International Commission on Radiological Protection. *ICRP Publication 103. Ann. ICRP*, **37** (2–4).

ICRP (International Commission on Radiological Protection) 2013 ICRP 119 Compendium of dose coefficients based on ICRP Publication 60. *Ann. ICRP* **42** (1).

Jaber, J. O. & Mousa, M. S. 2001 Evaluation of non-conventional water resources supply in Jordan. *Desalination* **136**, 83–92.

Jobbagy, V., Watjen, U. & Meresova, J. 2010 Current status of gross alpha/beta activity analysis in water samples: a short overview of methods. *J. Radioanal. Nucl. Chem.* **286**, 393–399.

JS 2001 Jordanian Drinking Water Standard (286/2001).

JS 2008 Jordanian Drinking Water Standard (286/2008).

Lloyd, J. W. & Pim, R. H. 1990 The hydrology and groundwater resources development of the Cambro-Ordovician sandstone aquifer in Saudi Arabia and Jordan. *J. Hydrol.* **121**, 1–20.

Lopes, I., Abrantes, J., Melo, J., Madruga, K. J. & Reis, M. 2010 LSC-quality assurance on gross alpha and beta measurements in waters. In: *Advances in Liquid Scintillation Spectrometry LSC 2010*, September 6–10, Paris, France.

Mott MacDonald 2009 Working Paper 07: Natural Groundwater Radioactivity in the Disi Aquifer. Issue and Revision Record: Report Reference 242392/WUD/09. Mott MacDonald/EIB/OPIC/Proparco.

Mousa, M. S. 2007 Water strategies and potential of desalination in Jordan. *Desalination* **203**, 27–46.

MWI/WAJ/MoH 2006 Official correspondence to the WHO Regional Centre for Environmental Health Action (CEHA). Translated and/or original Arabic text available on request from the authors.

NRPB (National Radiological Protection Board) 1998 *Living with radiation*. National Radiological Protection Board, Chilton, Didcot, UK.

Powell, J. H. 2014 Verbal comment provided to B. Smith, 15 September.

Powell, J. H. & Smith, B. 2011 Uranium mineralization and groundwater contamination by natural radionuclides in Late Cretaceous carbonate aquifers (Amman, Jordan). In: *10th Jordanian Geological Conference*, Amman, 2011.

Powell, J. H., Abdulkader, M. A. & Le Nindre, Y.-M. 2014 Cambrian stratigraphy in Jordan. *GeoArabia* **19** (3), 81–134.

Sanchez-Cabeza, J. A. & Pujol, L. 1995 A rapid method for the simultaneous determination of gross alpha and beta activities in water samples using a low background liquid scintillation counter. *Health Phys.* **68**, 674–682.

Schubert, M., Schuth, C., Michelsen, N., Rausch, R. & Al-Saud, M. 2011 Investigation and treatment of natural radioactivity in large scale sandstone aquifer systems. *Int. J. Water Res. Arid Environ.* **1**, 25–32.

Smith, B., Gedeon, R., Constantinou, G., Amro, H., Powell, J., Afrodisis, S., Hutchins, M., Constantinou, C. & Trick, J. K. 1998 Radioelements in groundwaters and post cretaceous sediments from the southern Mediterranean margin. In: *Proceedings: Water in the Mediterranean. Collaborative Euro-Mediterranean Research: state of the art, results and future priorities*, Istanbul, November 1997.

Tayyeb, Z. A., Kinsara, A. R. & Farid, S. M. 1998 A study of the radon concentrations in Jeddah (Saudi Arabia) and the associated health effects. *J. Environ. Radioact.* **38**, 97–104.

USEPA (United States Environmental Protection Agency) 1999 *Cancer Risk Coefficients for Environmental Exposure to*

Radioactivity. Federal Guidance Report No. 13. USEPA, Washington, DC.

USEPA (United States Environmental Protection Agency) 2005 *A Regulators' Guide to the Management of Radioactive Residuals from Drinking Water Treatment Technologies*. July 2005. EPA 816-R-05-004. USEPA, Washington, DC.

Vengosh, A., Hirschfeld, D., Vinson, D., Dwyer, G., Raanan, H., Rimawj, O., Al-Zoubi, A., Akkawi, E., Marie, A., Haquin, G., Zaarur, S. & Ganor, J. 2009 High naturally occurring radioactivity in fossil groundwater from the Middle East. *J. Environ. Sci. Technol.* **43**, 1769–1775.

Vengosh, A., Hirschfeld, D., Vinson, D., Dwyer, G., Raanan, H., Marie, A., Zaarur, S. & Ganor, J. 2014 Response to comment on 'high naturally occurring radioactivity in fossil groundwater from the Middle East. *Environ. Sci. Technol.* **48**, 9946–9947.

Wardam, B. 2013 *Should we drink from Disi Water?* https://bwardam.wordpress.com/2013/07/16/should-we-drink-from-disi-water/ (Accessed 1 February 2016).

WHO 1993 *Guidelines for Drinking Water Quality*, 2nd edn. World Health Organization, Geneva.

WHO 2004 *Guidelines for Drinking Water Quality*, 3rd edn. World Health Organization, Geneva.

WHO 2008 *Guidelines for Drinking-water Quality, 3rd edition, incorporating the first and second addenda*. World Health Organization, Geneva.

WHO 2011 *Guidelines for Drinking Water Quality*, 4th edn. World Health Organization, Geneva.

WHO/CEHA 2007 Letter from WHO/CEHA in its response to the MWI/WAJ/MoH (2006) Dated February 2007. Translated and/or original Arabic text available on request from the authors.

First received 20 October 2015; accepted in revised form 20 December 2015. Available online 24 February 2016