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Radioactivity in drinking water supplies in Western Australia

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Abstract

Radiochemical analysis was carried out on 52 drinking water samples taken from public outlets in the southwest of Western Australia. All samples were analysed for Ra-226, Ra-228 and Pb-210. Twenty five of the samples were also analysed for Po-210, and 23 were analysed for U-234 and U-238. Ra-228 was found in 45 samples and the activity ranged from <4.000 to 296.1 mBq L^{-1}. Ra-226 was detected in all 52 samples and the activity ranged from 3.200 to 151.1 mBq L^{-1}. Po-210 was detected in 24 samples and the activity ranged from 0.000 to 114.2 mBq L^{-1}. These data were used to compute the annual radiation dose that persons of different age groups and also for pregnant and lactating females would receive from drinking this water. The estimated doses ranged from 0.001 to 2.375 mSv y^{-1} with a mean annual dose of 0.167 mSv y^{-1}. The main contributing radionuclides to the annual dose were Ra-228, Po-210 and Ra-226. Of the 52 drinking water samples tested, 94% complied with the current Australian Drinking Water Guidelines, while 10% complied with the World Health Organization's radiological guidelines which many other countries use. It is likely that these results provide an overestimate of the compliance, due to limitations, in the sampling technique and resource constraints on the analysis. Because of the increasing reliance of the Western Australian community on groundwater for domestic and agricultural purposes, it is likely that the radiological content of the drinking water will increase in the future. Therefore there is a need for further monitoring and analysis in order to identify problem areas.

Keywords: Drinking water; Groundwater; Po-210; Ra-226; Ra-228; Western Australia

Background

Groundwater use in Australia

Australia's use of groundwater has increased significantly over recent decades. From 1983 to 1996 our national reliance on groundwater increased by nearly 90% and future use of groundwater is projected to rise, especially as surface water resources may become less available due to climate change and prolonged droughts (Geoscience Australia, 2013). Rainfall in the southwest (SW) of Western Australia (WA) has already declined by around 15% since the mid-1970s resulting in less surface runoff and reduced groundwater resources (Department of Environment, 2013). Climate models project that rainfall could decline further by about 7% and surface water yields are projected to decrease by about 24% by 2030 (Commonwealth Scientific and Industrial Research Organisation of Australia [CSIRO], 2009).

WA has extensive groundwater supplies, especially within the Perth Basin, where the majority of the population lives. The groundwater has been heavily exploited to provide public and private drinking water (DW) supplies for Perth and major regional centres such as Albany, Geraldton, Bunbury and Busselton. Approximately 66% of Perth's public DW supply comes from groundwater sources (Geoscience Australia, 2013) and some regional centres, such as Albany, Bunbury and Busselton are totally dependent on groundwater.

Groundwater is extracted from sediments, some of which contain radioactive deposits derived from uranium, thorium or potassium-40. There is very limited public information available about the levels of radioactivity in Australian groundwater (Lokan, 1998). Previous research by the Australian Radiation Laboratory, now known as the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) revealed that some WA DW supplies have significantly higher concentrations of Ra-226, Ra-228 and K-40 than those in other States of Australia (Cooper, 1989). A further survey by Efendi and Jennings (1994) found much higher levels of Rn-222 and Ra-226 in groundwater samples derived from gravels and igneous rock formations.

Groundwater salinity

Salinity is a growing concern in most parts of Australia, particularly in the SW of WA (Australian Academy of Science, 2004). The problem with groundwater salinity is that research has shown that there is a strong correlation between elevated levels of radium isotopes (Vengosh, 2006) and Pb-210 and Po-210 concentrations (Dickson and Herczeg, 1992) and salinity, as the hydrogeochemical condition has a tendency to mobilise and therefore has a significant role in the distribution of these radionuclides in groundwater (Dickson and Herczeg, 1992: Vengosh, 2006).

Thus there is potential for these radionuclides to increase in concentrations in groundwater resources as salinity levels in the SW of WA groundwater continue to rise and as pressure on them from agriculture, urban development and climate change increases. Already we are seeing a trend to exploit deeper aquifers as superficial aquifers are depleted by over use and climate change (Geoscience Australia, 2013). Groundwater from deeper aquifers is generally much older and is often oxygen-depleted and richer in radium isotopes (Vengosh, 2006). Many people believe that salinity is the most serious environmental threat that Australia faces (CSIRO, 2008) and therefore further monitoring of radionuclides in groundwater used for DW is warranted.

Australian Drinking Water Guidelines

The National Health and Medical Research Council and Natural Resource Management Ministerial Council (NHMRC and NRMMC) of Australia amended the Australian Drinking Water Guidelines (ADWG) and increased the radiological guideline value for DW from 0.1 mSv y^{-1} to 1.0 mSv y^{-1} in 2004 (NHMRC and NRMMC, 2004 and National Health and Medical Research Council and Natural Resource Management Ministerial Council of Australia, 2011). The current guideline value for radiological quality of DW requires that the total estimated dose per year from all radionuclides, excluding the dose from K-40, should not exceed 1 mSv. The dose coefficients for ingestion of selected radionuclides are provided by the International Commission on Radiological Protection [ICRP], 1996and the NHMRC

(NHMRC and NRMMC, 2004 and National Health and Medical Research Council and Natural Resource Management Ministerial Council of Australia, 2011). The guidelines provide a procedure for monitoring DW for radionuclides and they include recommendations for the routine testing of all groundwater supplies every two years for radiological contamination and more often if the guideline value is exceeded. Because of WA's heavy and increasing reliance on groundwater supplies for its DW, this investigation was undertaken to fill the gap in public knowledge about the radioactivity levels in DW supplies.

Methods

Sampling

The DW samples were collected at 52 sites covering the SW, Goldfields, Great Southern, Peel, Kimberley and Perth Metropolitan Area. Fig. 1 shows the land mass and the DW sampling sites in the SW of WA. The samples were obtained at public facilities such as schools and parks and were derived originally from groundwater sources (49) or surface water reservoirs (3). The samples were collected in 1 L polyethylene bottles. Ideally the samples should have been acidified to at least 0.2 M HNO_3 (Katzlberger et al., 2001) to prevent the loss of radionuclides through adsorption to the walls of the containers. This was not possible for our samples as they were to be analysed at the University of Vienna and there are restrictions imposed by airlines on the transport of hazardous substances. Consequently the results of the analysis are likely to provide underestimates of the Pb-210, Po-210, radium isotopes and possibly also the uranium content of the water samples. However, prior to analyses the sample bottles were washed out twice with 10 mL of concentrated HNO_3 to correct and minimise the adsorption effects of Pb-210, Po-210, radium isotopes and uranium isotopes on the walls of the bottles and the contents were added to the water sample awaiting radiochemical analysis. The DW samples selected in this study had already undergone treatment processes to ensure compliance with chemical parameters outlined within the ADWG. These processes would ensure that concentrations of iron and manganese would be low and exclude the possibility of some radionuclides precipitating out of solution during prolonged and unpreserved storage.

Analysis

The radiochemical analysis of all of the DW samples was carried out at the Institut für Anorganische Chemie at the University of Vienna. The procedures used have been described previously by Wallner, 2002 and Wallner et al., 2009 and Wallner and Jabbar (2010). The process involved the extraction of Ra-226, Ra-228 and Pb-210 from the initial DW sample using the radium selective 3 M Radium Rad Disk. The second stage of the procedure involved the spontaneous deposition of Po-210 from the remaining solution, and the third stage, the measurement of uranium after ion exchange and microprecipitation.

Determination of radium isotopes and Pb-210 by LSC

The radium isotopes Ra-226 and R-228 were isolated by filtering the sample through a membrane loaded with element-selective particles (Empore™ Radium Disks). Pb-210 is co-extracted during this procedure. The extracted nuclides were eluted with 0.25 M alkaline EDTA solution which was evaporated to about 2–3 mL and then mixed with the LSC cocktail HiSafe™ III. The radium isotopes and Pb-210 were measured with pulse-shape analysis using a Quantulus™ 1220 (Wallac Oy®, Finland, now Perkin Elmer®).

The Quantulus™ 1220 has advantages of having an extremely low background for performing radioactivity measurements, a counting efficiency of close to 100% for alpha emitters and very good alpha/beta-separation/discrimination capabilities (Schonhofer and Wallner, 2001). The Quantulus™ can detect beta and alpha radiation, Cerenkov radiation, X-rays, Auger electrons, luminescence and gamma radiation. The Quantulus™ has two photomultiplier tubes (PMTs) to detect background events and two other PMTs for coincident sample counting (the background PMTs are operated in anti-coincidence with the sample PMTs). With Quantulus™, pulse-shape analysis (PSA) facilitates the simultaneous measurement of pure alpha and beta spectra when counting samples containing alpha as well as beta emitters (Perkin Elmer Life Sciences, 2002). Light pulses following alpha decay have a longer life-time than those following beta decay and so by discriminating by the duration of the generated light pulses the two sorts of emitters in a mixed sample can be electronically distinguished. However, there is also a disadvantage connected with LSC: the alpha-peaks are rather broad due to a very poor energy resolution (compared to a spectrum measured with a semiconductor detector). This means that a spike cannot be added to the sample for yield determination. Therefore, the yield of the chemical procedure has to be determined on separate samples and it must be guaranteed that this yield is reproducible. This was the case with the investigated water samples due to the highly reproducible 100% Ra and Pb extracting Radium Disks.

Chemical yields between 95 and 100% were obtained by multiple processing of samples with known Ra-226 and Pb-210 activity concentrations. The counting efficiency for Ra-226 was 100% while the counting efficiency for Ra-228 was determined with a standard solution (Ra-228 separated from a Th-232 solution by ion exchange) and found to be (57 ± 3) %. The counting efficiency for Pb-210 was approximately 100%: in fact the counting efficiency for beta emitters in this energy range is about 50%, but Pb-210 emits 200 betas/electrons per 100 decays due to conversion (Wallner, 2002).

The lower limit of detection (LLD) was calculated after Currie (2004) for Ra-226 and Ra-228 was 1 mBq per sample (counting time 1000 min) and 4 mBq per sample, respectively. The LLD for Pb-210 was 2 mBq sample^{-1}. The procedure was verified on in-house standards (mineral waters with known activity concentrations).

Determination of Po-210 and uranium by α-spectroscopy

Po-208 and U-232 tracers were added to the filtrate from the radium and lead separation step. After evaporation to dryness the residue was dissolved in 30 mL distilled water and 15 mL conc. HCl, put into an ultrasonic bath for 30 s and evaporated again. Finally it was taken up in 0.8 M HCl and a spatula of ascorbic acid was added in order to reduce iron. A copper planchette rinsed with 2 M HCl was added to the solution. During 2 h of stirring at about 80–90 °C, polonium was deposited spontaneously on the Cu planchette (WHO, 1966), which was measured with a PIPS (Passivated Implanted Planar Silicon) detector (7401 VR, Canberra/Packard). With a chemical yield of 25–30% and a counting time of 1000 min, the LLD of Po-210 was estimated to be 2 mBq sample^{-1}.

The solution from which Po-210 had been separated was evaporated to dryness. After that the residue was transformed into chlorides with half-concentrated HCl, the solution was evaporated again and then the residue was taken up in 70 mL 8 M HCl. Uranium was separated from Th and Ca by anionic exchange on Dowex 1 × 2 (100–200 mesh) from 8 M

HCl solution (Krtil et al., 1975) and eluted with 0.1 M HCl. Sources for α-spectrometry were prepared by microprecipitation of the uranium with neodymium fluoride (Hindman, 1983 and Joshi, 1985). With counting times of 2000 min, using a surface barrier detector, an LLD of 0.5 mBq L^{-1} U-238, i.e. 0.04 μg L^{-1} $U_{nat.}$, could be achieved.

Results

The Ra-226, Ra-228 and Pb-210 activity concentrations were determined for each of the 52 DW samples. The Po-210, U-234 and U-238 activity concentrations were measured in only a representative subset of the samples due to the longer times involved in sample preparation and analysis. The arithmetic means were calculated after Currie (2004). A summary of the individual radioactivity concentrations of these isotopes is presented in Table 1. The full data set has been reproduced from Walsh (2010).

The annual radiation doses received by the community from these radioisotopes in the DW at the 52 sites in WA have been calculated using the US National Academies, Institute of Medicine, Food and Nutrition Board's (NAIMFNB) Recommended Adequate Intakes for Water (2004) shown in Tables 2 and 3, together with the measured radioactivity concentrations and the ICRP (1996) radiation dose coefficients for ingestion. The formula used for this purpose is presented in Equation (1).

Adequate intakes (AI) for DW have since been adopted by the NHMRC and the New Zealand Ministry of Health (MOH) that are very similar to those of the NAIMFNB cited in this paper (NHMRC and MOH, 2013).

$$\begin{aligned}\text{Annual Dose}\left(\text{mSv year}^{-1}\right) = &\ \text{Dose Per Unit Intake in mSv Bq}^{-1}(\text{Dose Coefficient})\\ &\times \text{Annual Drinking Water Consumption}\left(\text{L year}^{-1}\right)\\ &\times \text{Radionuclide Concentration}\left(\text{Bq L}^{-1}\right)\end{aligned}$$

Equation (1): Formula used to calculate annual radiation dose received from the consumption of drinking water.

Source: NHMRC and NRMMC, 2004 and National Health and Medical Research Council and Natural Resource Management Ministerial Council of Australia, 2011.

The combined annual radiation doses (mSv y^{-1}) from all the radionuclides in the DW were also calculated for the different age groups. A summary of the mean annual doses for all age groups and the combined annual dose (mSv y^{-1}) for all age groups is given in Tables 4 and 5.

A summary of annual radiation doses recieved by different age groups from combined radionuclides and from polonium-210 found in DW supplies in the SW of WA are presented in Tables 6 and 7 respectively.

Discussion

Overall results

Table 1 shows that there is a wide variation in the radioactivity concentrations in WA DW supplies. Most of the activity comes from Ra-228, Ra-226 and Po-210. The Ra-228 activities are due to the presence of thorium in WA granites (Walsh and Jennings, 2002:Geoscience Australia, 2012) and these levels indicate a need to monitor regularly for this radioisotope as well as for Ra-226 a parent of Po-210. Overall Ra-228 is a larger contributor to the annual dose for all age groups than Ra-226 as shown in Table 4. This finding is similar to DW surveys carried out by the US EPA and the US Geological Survey in 1988 and 1998 respectively (Office of Environmental Health Hazard Assessment and California Environmental Protection Agency, 2006). Table 6 shows that some WA DW supplies do have the potential to exceed the annual radiological guideline value outlined within the ADWG for adolescents and infants.

Overall we found that 94% of the 52 WA DW samples complied with the Australian radiological safety guidelines outlined in the ADWG (NHMRC and NRMMC, 2004 and National Health and Medical Research Council and Natural Resource Management Ministerial Council of Australia, 2011). However it should be noted that the Australian DW guideline is 10 times higher than the value adopted by many other industrialised countries, including Canada (2010), the USA (2000), the European Union (2012) and the World Health Organization [WHO] (2006). Thus if the guidelines recommended by the WHO were applied, then only 10% of the WA DW samples would comply and only 6% of the samples would comply with the US EPA radiological guideline for DW (US EPA, 2000). The main reason for this is the high levels of Ra-228 in the WA DW samples and also the presence of Po-210 in some of the samples.

If we look at the WA results from the standpoint of infants only 8% of the DW samples would comply with the WHO guidelines. For adolescents the situation is better with 23% of the DW samples complying. In fact, this is probably an overestimate of the compliance situation because the activity analysis was incomplete for half the sites and the samples were not acidified on collection to prevent isotope loss through adsorption. These results are sufficiently concerning to indicate the need for a thorough nationwide study of radioactivity in DW supplies. Some further investigations and remedial action may be necessary in those locations where elevated levels are discovered.

Polonium-210

It is worth noting that Po-210 was detected in 24 out of 25 of the DW samples and its contribution to the annual dose was greater than that of Ra-226. However, there is little data on Po-210 (ARPANSA, 2008: Seiler and Weimels, 2012) and on the effects of human exposure to Po-210 (Seiler and Weimels, 2012). Po-210 concentrations in groundwater are generally low due to geochemistry and microbial processes that mobilise only small percentages of the Po-210 present. However, these concentrations are sufficient to contribute significant doses and exceed safe levels in DW (ARPANSA, 2008: Seiler and Weimels, 2012). Seiler and Weimels (2012) have discovered that Po-210 is a possible cause of leukaemia as it accumulates in the reproductive organs and furthermore that most childhood leukaemias originate before birth and are passed on from the mother to child. The authors are of the view that the lack of data on Po-210 is due to the fact that it has not been looked for very much in the past. In this regard it is also worth noting that up until 2000 the US EPA protocol for the monitoring for combined radium-226 and radium-228. It was assumed that radium-226 and gross alpha levels could be used for to screen for radium-228. This assumption was eventually proved to be incorrect (US EPA, 2001).

Conclusions

A study of DW in WA was undertaken, based on 52 water samples collected from public outlets primarily in the SW of WA. This study has found that the estimated annual radiation dose from DW supplies ranged from 0.001 to 2.375 mSv y^{-1} with a mean of 0.167 mSv y^{-1}. The main contributions to this annual dose came from Ra-228, Po-210 and Ra-226. The dose from Ra-228 was approximately 6.4 times greater than that of Ra-226. The dose from Po-210 was unexpected and was greater than the dose from Ra-226.

Of the 52 DW samples tested:

- 94% complied with the current radiological guideline value within the ADWG.
- 10% of the samples complied with the WHO radiological guideline which many other countries follow.
- 6% of the samples complied with the US EPA radiological guideline for DW.

It is likely that these results represent an overestimate of the compliance because of limitations in the sampling technique and the fact that only half of the DW samples were analysed for all seven key isotopes. It is also probable that the radiological quality of DW supplies in WA will decline in the future due to the increasing dependence on groundwater, which is impacted by climate change and development.

It is worth noting that the dose assessments determined in this study used different values for adequate water intakes of DW for adults, adolescents and infants recommended by the US

NAIMFNB compared to the adequate water intakes of DW recommended by the ADWG which is 2 L day^{-1} for adults only. In addition it may also be worth noting that in many areas in WA, particularly in arid areas, actual adequate DW intakes for many people (of all ages) will be significantly higher than the 2 L recommended in the ADWG. In this regard the NHMRC of Australia has recently published recommended adequate water intakes for DW similar to those published by the US NAIMFNB (NHMRC and MOH, 2013).

Therefore the authors recommend that a comprehensive public survey of DW supplies should be carried out in WA to check these findings and identify any sources that have unacceptably high levels of radiological contamination and include Po-210 in the routine radiochemical analyses of DW samples. This view is supported by ARPANSA as it believes that Australian DW may contain higher levels of radioactivity and radiation doses that are considerably higher than the world-wide average and therefore a comprehensive study of Australian DW may be warranted (Australian Radiation Protection and Nuclear Safety Agency, 2005 and Australian Radiation Protection and Nuclear Safety Agency, 2008). Furthermore, the authors recommend that the NHMRC should review the ADWG and consider the doses that children and adolescents are likely to receive before setting future guidelines for DW. There is a need to carefully assess the average daily DW intake for various age groups in all climate zones of Australia. The precautionary principle should be applied in choosing a daily intake and a radiological guideline for DW.

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References

Australian Academy of Science, January 2004. Monitoring the White Death e Soil Salinity. NOVA Science in the News. http://www.science.org.au/nova/032/032key.html.

Australian Radiation Protection and Nuclear Safety Agency, October 2005. Environmental Radioactivity Monitoring in Australia 2003 and 2004. Technical report of the Australian Radiation Protection and Nuclear Safety Agency. Australian Government. Technical report series no. 143.

Australian Radiation Protection and Nuclear Safety Agency, August 2008. The Radioactivity of Some Australian Drinking Waters. Technical report of the Australian Radiation Protection and Nuclear Safety Agency. Australian Government. Technical report series no. 148.

Canada Health, December 2010. Internet Extract. Guidelines for Canadian Drinking Water Quality - Guideline Technical Document Radiological Parameters. http://www.hc-sc.gc.ca/ewh-semt/pubs/water-eau/radiological_para-radiologiques/index-eng.php

Cooper, M.B., 1989. The radiological quality of Australian drinking water supplies. Unpublished raw data. Lecture and Workshop, 28 June 1989. In: 4th Annual Conference of the Australian Radiation Protection Society (Inc), Perth, Western Australia. 26th to 29th June 1989, ARPS (Inc), Verdun Street, Nedlands, Western Australia 6009.

CSIRO, October 2008. Salinity. CSIRO Salinity Fact Sheet. http://www.google.com.au/url?sa¼t&rct¼j&q¼&esrc¼s&frm¼1&source¼web&cd¼2&ved¼0CDoQFjAB&url¼http%3A%2F%2Fwww.csiro.au%2Fcontent%2Fw%2Fmedia%2FCSIROau%2FDivisions%2FCSIRO%2520Land%2520and%2520Water%2FSalinityFactsheet_CLW_pdf%2520Standard.pdf&ei¼S9yaUrbRO4eXigeCrYGwCA&usg¼AFQjCNHPvlcCC4P93642hWMX1Uwv7imKtw.

CSIRO, 2009. Internet Extract. Groundwater Yields in South-West Western Australia. A report to the Australian Government from the CSIRO South-West Western Australia Sustainable Yields Project. CSIRO Water for a Healthy Country Flagship, Australia. http://www.clw.csiro.au/publications/waterforahealthycountry/swsy/pdf/SWSY-Main-Report-Groundwater.pdf.

Currie, L.A., 2004. Uncertainty in Measurements Close to Detection Limits: Detection and Quantification Capabilities. IAEA TECDOC-1401, pp. 9-33.

Department of Environment, 2013. Internet Extract. Western Australia Climate Change Impacts in WA. Australian Government, Department of Environment. http://www.climatechange.gov.au/climate-change/climate-science/climatechange-impacts/western-australia.

Department of Land Information, 2006. Internet Extract. Map of Regional Development Regions of Western Australia. Department of Land Information in Perth, Government of Western Australia. http://www.dlgrd.wa.gov.au/statisticInfo/_pubBin/map_RegionalDevelop.pdf.

Dickson, B.L., Herczeg, A.L., 5 March 1992. Naturally-occurring radionuclides in acid e saline groundwaters around Lake Tyrell, Victoria, Australia. Chem. Geol. 96 (1-2), 95-114. The Geochemistry of Acid Groundwater Systems. http://www.sciencedirect.com/science/article/pii/000925419290123M

Efendi, Z., Jennings, P., 1994. An assessment of the environmental radiation dose for the residents of the Perth Metropolitan area. Radiat. Prot. Aust. 12 (1), 8-12.

European Commission, 2012. Council Directive. Laying down requirements for the protection of the health of the general public with regard to radioactive substances in water intended for human consumption. Brussels, 28.3.2012 COM (2012) 147 final 2012/0074 (NLE). http://ec.europa.eu/energy/nuclear/radiation_protection/doc/2012_com_147.pdf.

Geoscience Australia, 2012. Internet Extract. Thorium. Department of Resources, Energy and Tourism, Australian Government. http://www.australianminesatlas.gov.au/aimr/commodity/thorium.html.

Geoscience Australia, 30 July 2013. Internet Extract. Groundwater Use. Australian

Government, Geoscience Australia. http://www.ga.gov.au/groundwater/basics/groundwater-use.h

Hindman, D.F., 1983. Neodymium fluoride mounting for spectrometric determination of uranium, plutonium and americium. Anal. Chem. 55, 2460-2461.

International Commission on Radiological Protection, 1996. Age-dependant doses to members of the public from intake of radionuclides: part 5 compilation of ingestion and inhalation dose coefficients. ICRP Publication 72 Ann. ICRP 26 (1). Oxford Pergamon Press.

Joshi, S.R., 1985. Lanthanum fluoride coprecipitation technique for the preparation of actinides for alpha-particle spectrometry. J. Radioanal. Nucl. Chem. 90 (2), 409-414.

Katzlberger, C., Wallner, G., Irlweck, K., 2001. Determination of 210Pb, 210Bi and 210Po in natural drinking water. J. Radioanal. Nucl. Chem. 249 (1), 191-196.

Krtil, J., Mencl, J., Moravec, A., 1975. The sorption of uranium on strongly basic anion-exchange resins I. The values of distribution ratios in HCl and HNO3 media. J. Radioanal. Nucl. Chem. Lett. 21, 115-120.

Lokan, K.H., 1998. Drinking water quality in areas dependent on groundwater. Radiat. Prot. Australas. 15 (1), 11-14.

National Academies, Institute of Medicine, Food and Nutrition Board, 2004. Dietary Reference Intakes for Water, Potassium, Sodium, Chloride and Sulphate. Food and Nutrition Board Institute of Medicine. The National Academies Press, Washington, DC. http://www.nal.usda.gov/fnic/DRI/DRI_Water/water_full_report.pdf. December 2012.

National Health and Medical Research Council, Natural Resource Management Ministerial Council of Australia, 2004. Australian Drinking Water Guidelines 6, 2004, National Water Quality Management Strategy. Commonwealth of Australia. http://www.nhmrc.gov.au/_files_nhmrc/publications/attachments/eh34_adwg_11_06.pdf http://www.nhmrc.gov.au/_files_nhmrc/publications/attachments/adwg_11_06_chapter_7.pdf.

National Health and Medical Research Council, Natural Resource Management Ministerial Council of Australia, October 2011. National Water Quality Management Strategy Australian Drinking Water Guidelines 6, vol. 1, ISBN 1864965118. http://www.nhmrc.gov.au/_files_nhmrc/publications/attachments/eh52_aust_drinking_water_guidelines_update_120710_0.pdf.

National Health and Medical Research Council of Australia, Ministry of Health New Zealand, 2013. Nutrient Reference Values for Australia and New Zealand. Water. National Health and Medical Research Council. Australian Government. http://www.nrv.gov.au/nutrients/water.htm.

Office of Environmental Health Hazard Assessment, California Environmental Protection Agency, March 2006. Public Health Goals for Chemicals in Drinking Water Radium-226 and Radium-228. http://www.oehha.ca.gov/water/phg/pdf/PHGradium030306.pdf.

Perkin Elmer Life Sciences, 2002. Product Information Brochure. Quantulus Measuring Extremely Low Levels of Environmental Alpha and Beta Radiation. Perkin Elmer Life Sciences . http://las.perkinelmer.ca/Content/RelatedMaterials/Quantulus_Brochure.pdf.

Schonhofer, F., Wallner, G., 2001. Very rapid determination of Ra-226, Ra-228 and Pb-210 by selective adsorption and liquid scintillation spectrometry. Radioact. Radiochem. 12 (2), 33-38.

Seiler, R.L., Weimels, J.T., September 2012. Occurrence of 210Po and biological effects of low-level exposure: the need for research. Environ. Health Perspect. 120 (9), 1230-1237.

United States Environmental Protection Agency, 2000. Federal Register e National Primary Drinking Water Regulations; Radionuclides; Final Rule. Internet Extract, Federal Register Part II 40 CFR Parts 9, 141, 142, vol. 65, no. 236, 7 December 2000, pp. 76707-76753. March 2001.

United States Environmental Protection Agency, Office of Water, 2001. Ground Water and Drinking Water - Radionuclides in Drinking Water. Internet Extract, pp. 1-4. http://epa.gov/safewater/standard/pp/radnucpp.html (last updated 02.02.01.).

Vengosh, A., May 2006. Rooting out radioactive groundwater. Geotimes. http://www.geotimes.org/may06/feature_RadioactiveWater.html. July 2009.

Wallner, G., 2002. Determination of 228Ra, 226Ra and 210Pb in drinking water using liquid scintillation counting. In: Mobius, Siegurd, Noakes, John, Schonhofer, Franz (Eds.), LSC 2001, “Advances in Liquid Scintillation Spectrometry”, pp. 269-274.

Wallner, G., Herincs, E., Ayromlou, S., 2009. Determination of natural radionuclides in drinking water from the Waldviertel, Austria. In: Eikenberg, J., Jaggi, M., Beer, H., Baehrle, H. (Eds.), International Conference on Advances in Liquid Scintillation Spectrometry 2008 (Davos, Switzerland), pp. 269-274. Radiocarbon, Tucson, USA, (2009), 345-352.

Wallner, G., Jabbar, T., 2010. Natural radionuclides in Austrian bottled mineral waters. J. Radioanal. Nucl. Chem. 286, 329-334.

Walsh, M., Jennings, P., December 2002. A study of environmental radon levels in rammed earth dwellings in the southwest of Western Australia. Radiat. Prot. Aust. J. Australas. Radiat. Prot. Soc. Inc. 19 (2).

Walsh, M., 2010. Naturally Occurring Radionuclides in Drinking Water Supplies in the South West of Western Australia and Their Potential Impact on Human Health (PhD thesis). Murdoch University Perth,

Western Australia. World Health Organization (WHO), 1966. Methods of Radiochemical Analysis. WHO. World Health Organization (WHO), Geneva, 2004. Uranium.

World Health Organization, 2006. Recommendations, third ed. Guidelines for Drinking-Water Quality. First addendum to third edition, vol. 1. http://www.who.int/water_sanitation_health/dwq/gdwq3rev/en/index.

html http://www.who.int/water_sanitation_health/dwq/gdwq0506_9.pdf August 2009.

Figure 1. Map of the southwest of Western Australia showing DW sampling sites.

Source: Department of Land Information Government of WA (2006).

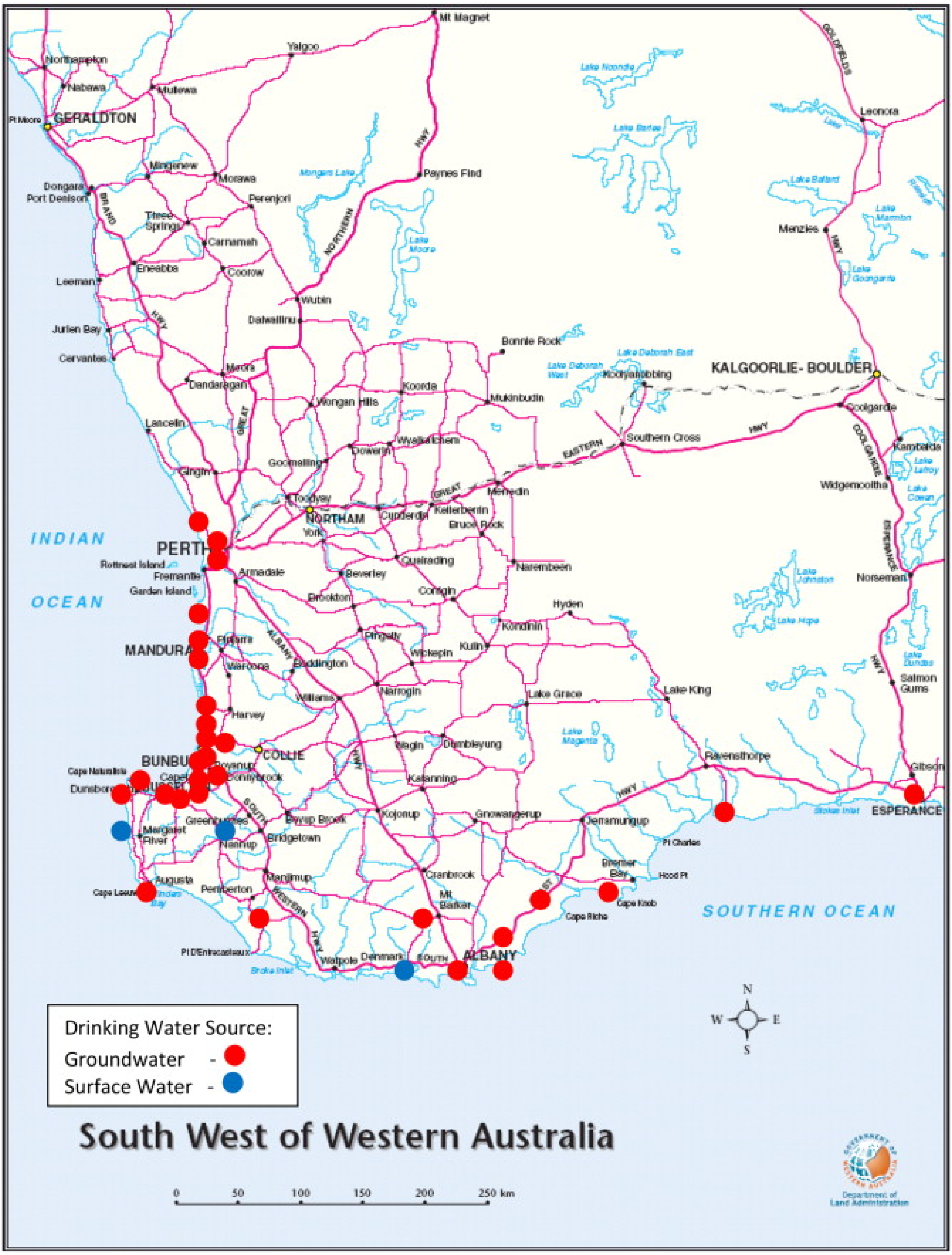

Table 1. Summary of individual radionuclide concentrations (mBq L^{-1}) found in selected Western Australian public drinking water supplies

Radionuclide	Arithmetic mean	Number of samples analysed	Number of times detected	Minimum value	Maximum value
Ra-226	32.6	52	52	3.2	151.1
Ra-228	47.3	52	45	<LLD	296.1
Pb-210	0.7	52	6	<LLD	13.4
Po-210	24.2	25	24	0.0	114.2
U-234	3.1	23	20	0.0	12.8
U-238	2.3	23	20	0.0	14.3

Table 2. US National Academies, Institute of Medicine, Food and Nutrition Board recommended adequate water intake for infants (in L).

Age	Average of human milk consumed per day	Adequate intake for total water per day	Water obtained from drinks per day
Infants 0–6 months	0.7 L	0.7 L assumed to be from human milk (87% of the volume of human milk exists as water)	n/a
Infants 7–12 months	0.8 L	0.8 L from human milk and complementary food and beverages	0.6 L as total fluid, including formula, juices and drinking water

Source: US NAIMFNB (2004).

Table 3. US National Academies, Institute of Medicine, Food and Nutrition Board recommended adequate water intake for adults, adolescents, children and pregnant and lactating females (in L).

Age group		Total water intake per day (including water contained in food)	Water obtained from drinks per day
Children	1–3 years	1.3 L	0.9 L
Children	4–8 years	1.7 L	1.2 L
Boys	9–13 years	2.4 L	1.8 L
Girls	9–13 years	2.1 L	1.6 L
Boys	14–18 years	3.3 L	2.6 L
Girls	14–18 years	2.3 L	1.8 L
Adults	Men	3.7 L	3.0 L
	Women	2.7 L	2.2 L
Females	Pregnant	3.0 L	2.3 L
	Lactating	3.8 L	3.1 L

Source: US NAIMFNB, (2004).

Table 4. Summary of annual dose (mSv y^{-1}) for All age groups from individual radionuclides found in selected Western Australian public drinking water supplies.

Radionuclide	Arithmetic mean	Number of samples	Minimum value	Maximum value
Ra-226	0.019	52	0.001	0.215
Ra-228	0.121	52	<0.001	2.274
Pb-210	0.001	52	<0.001	0.029
Po-210	0.026	25	<0.001	0.760
U-234	<0.001	23	<0.001	0.001
U-238	<0.001	23	<0.001	0.001

Table 5. Summary of combined annual dose (mSv y^{-1}) for all age groups from combined lead-210, polonium-210, radium-226, radium-228, uranium-234 and uranium-238 concentrations found in selected Western Australian public drinking water supplies.

Arithmetic mean	Number of samples	Minimum value	Maximum value	Standard deviation
0.167	52	0.001	2.375	0.250

Table 6. Summary of annual dose (mSv y^{-1}) for different age groups from combined lead-210, polonium-210, radium-226, radium-228, uranium-234 and uranium-238 concentrations found in selected Western Australian public drinking water supplies.

Age group		Arithmetic mean	Minimum value	Maximum value	Standard deviation
Adults		0.062	0.002	0.248	0.055
15 years		0.303	0.009	1.581	0.297
10 years		0.159	0.003	0.797	0.151
5 years		0.103	0.002	0.466	0.094
1 year		0.119	0.002	0.521	0.110
3 months		0.480	0.007	2.375	0.455
Females	Pregnant	0.047	0.001	0.190	0.042
	Lactating	0.064	0.002	0.256	0.057

Table 7. Summary of annual dose (mSv y^{-1}) for different age groups from polonium-210 concentrations found in selected Western Australian public drinking water supplies.

Age group		Arithmetic mean	Minimum value	Maximum value	Standard deviation
Adults		0.015	0.000	0.150	0.031
15 years		0.018	0.000	0.173	0.036
10 years		0.020	0.000	0.195	0.040
5 years		0.022	0.000	0.220	0.045
1 year		0.030	0.000	0.293	0.061
3 months		0.077	0.000	0.760	0.157
Females	Pregnant	0.012	0.000	0.115	0.024
	Lactating	0.016	0.000	0.155	0.032