WHO Guidelines for Drinking-water Quality

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Acknowledgements

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The safety and accessibility of drinking-water are major concerns throughout the world.

Health risks may arise from water consumption (e.g. infectious agents, toxic chemicals, radioactivity).

Improving access to safe drinking-water can result in tangible improvements to health.
The quality of water, whether used for drinking, domestic purposes, food production or recreational purposes, has an important impact on health.
Radioactivity in Drinking-water: awareness has increased

Radium salt in water

Marketing for ‘radioactive’ water
Radionuclides in water supplies

- Natural radionuclides found in water
  - Potassium ($^{40}$K),
  - Thorium and uranium decay series, in particular radon ($^{222}$Rn) and radon progeny; uranium ($^{234}\text{U}$, $^{235}\text{U}$ and $^{238}\text{U}$); radium ($^{226}\text{Ra}$, $^{228}\text{Ra}$); lead ($^{210}\text{Pb}$)

- Human-made radionuclides in water: usually extremely low levels from nuclear establishments, medicine or industry, past releases
The WHO GDWQ are mentioned in the BSS in Section 5 on existing exposure situations

1. Introduction (1.1 – 1.55)
2. Gral. requirements for protection and safety (2.1 – 2.52)
3. Planned exposure situations (3.1 – 3.184)
4. Emergency exposure situations (4.1 – 4.21)
5. Existing exposure situations (5.1 – 5.33)

The WHO GHWQ refer to the BSS in its Chapter 9
Existing exposure situations

- Scope (5.1)
- Generic requirements (5.2 – 5.5)
- Public exposure (5.6 – 5.23)
- Occupational exposure (5.24 – 5.33)
BSS requirements regarding exposure due to radioactivity in food and water (5.22 and 5.23)

- The regulatory body or other relevant authority shall establish specific reference levels for exposure due to radioactivity in food, drinking water, and other commodities, each of which shall typically be expressed as, or be based on, an annual effective dose that does not exceed a value of about 1 mSv.

- They have to consider the guideline levels for:
  - Radionuclides contained in drinking water published by the WHO (i.e. GDWQ)
  - Radionuclides in food traded internationally published by the Joint FAO/WHO Codex Alimentarius Commission (i.e. Codex Alimentarius)
Reference level – what does it mean?

- “…a reference level (RL) that generally does not exceed a value of approximately 1 mSv”

- RL is a level of dose above which it is not appropriate to plan to allow exposures to occur and below which optimization of protection and safety would continue to be implemented.
WHO Guidelines for Drinking-water quality are not applied during radiation emergencies

- Other international radiation safety standards are considered in such situations:

  - General Safety Requirements GSR Part 7
  - General Safety Guide GSG-2 (provides operational intervention levels - OILs)
These topics will be addressed today during plenary discussions and breakout sessions.
Radiological aspects

- Radiological risks are normally **small** compared with the risks from microorganisms and chemicals that may be present in drinking-water.

- Except in extreme circumstances, the radiation dose resulting from the ingestion of radionuclides in drinking-water is **much lower** than that received from other sources of radiation.

- When considering what action to take in assessing and managing radiological risks, care should be taken to ensure that scarce resources are not diverted away from other, more important public health concerns.
The WHO Guidelines on DWQ have adopted the LNT model-approach

- Current **radiological protection system** based on the assumption that any exposure to radiation involves some level of risk
  - linear relationship between exposure and risk, with no dose level below which there is no risk (i.e. linear non-threshold: LNT model)

- For prolonged exposures (e.g., ingestion of drinking-water containing radionuclides over extended periods of time), evidence of an increased cancer risk in humans is available at doses around 50-100 mSv
The WHO Guidelines on DWQ have considered the ICRP recommendations

- In planned exposure situations, it is prudent to restrict the prolonged component of the individual dose to 0.1 mSv in any given year (ICRP, 2000)

- The WHO Guidelines for DWQ adopted a pragmatic and conservative approach for both natural radionuclides and human-made radionuclides, with an individual dose criterion (IDC) of 0.1 mSv from 1 year’s consumption of drinking-water, regardless the origin of the radionuclides
Today we will focus on Chapter 9
### WHO Guidelines for Drinking-water Quality

<table>
<thead>
<tr>
<th>Aim</th>
<th>Protection of human health</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>– Support setting of national standards and regulations</td>
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</table>

<table>
<thead>
<tr>
<th>Target Audience</th>
<th>Regulators + (water suppliers, practitioners . . .)</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Approach</th>
<th>Best available evidence - science and practice</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Risk-benefit philosophy (advisory in nature)</td>
</tr>
<tr>
<td></td>
<td>Advisory in nature allowing local adaptation considering overall health protection strategies</td>
</tr>
<tr>
<td></td>
<td>– Social, cultural, economic and environmental context</td>
</tr>
<tr>
<td></td>
<td>Preventive incorporating multiple barriers</td>
</tr>
<tr>
<td></td>
<td>Incremental improvement</td>
</tr>
</tbody>
</table>

**Evidence-based**

[Guidelines for Drinking-water Quality, Fourth Edition]

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Workshop on Control of Public Exposure in Compliance with the International BSS, Cape Town, South Africa | May 19, 2016
A flagship normative publication of WHO

“Immediate and wide recognition as essential aids to the improvement of water quality and treatment”

Guidelines for Drinking-water Quality, 4th Edition, 2011 -
Demand for the document is among the highest and most sustained of all WHO publications
Core Recommendations
Framework for Safe Drinking-water

- Establish national water quality standards on relevant waterborne hazards
- Undertake site-specific local risk assessment and management from catchment to consumer
- Verify water safety through independent tests and audits

**Health-based targets**
(National regulatory body)

**Water Safety Plan**
(Water utility)

**Independent surveillance**
(Surveillance agency)
WSP Overview

A process that:

- Identifies risks from catchment to consumer
- Prioritises risks
- Mitigates risks through control measures
- Risk based – focus limited resources on highest risks to water safety

89 countries implementing WSPs
**GDWQ - all types of drinking-water source**

- Huge variation in types of source from large well-run municipal supplies to small resource poor rural sources that may supply just a few people.

- Emphasises do what you can and aim for continuous improvement.

- Provides guidance on priorities for those with few resources.

- Not just about measuring standards at the end of pipe.
Sources of Drinking-Water

There are three main sources of water used for deriving drinking water. These are:

- **Groundwater**, often well protected from surface contamination but not always.

- **Rivers**, vulnerable to many sources of contamination.

- **Wastewater discharges**.

- **Reservoirs and lakes**, often river fed.
Drinking-Water Production

- Groundwater may receive very limited treatment, particularly if from a well-protected, stable source.

- Surface water will usually receive greater levels of treatment, particularly for larger municipal supplies, following the multi-barrier approach to ensuring drinking-water safety. Can include coagulation and sedimentation, and filtration that in modern systems in developing countries will include membranes.

- Small supplies receive much more limited treatment but increasingly point of use devices available.
Drinking-water Management

- Drinking-water can be delivered by large municipal supplies, often with significant resources, particularly in developed countries.

- There are also many small rural individual or community supplies that are often poorly resourced and very basic.

- This means that the capability to monitor or screen for contaminants is in general variable, and for radioactivity it usually varies from limited to none.

- The same applies to treatment options except many large supplies in developed countries have advanced treatment.
Radioactivity in drinking-water

- No distinction between natural and artificial radionuclides. However, management may differ (point of control and ability to control).

- Natural usually of greater concern for drinking-water.

- Best controlled by prevention but need to ensure that public perception of risk and sensitivity to drinking-water quality does not divert resources away from more important contaminants.

- Guidance is based on a screening approach.
Screening Values

- Screening values based on committed effective dose of 0.1 mSv from 1 year’s consumption of 2 litres per day
  - 0.5 Bq/litre for gross alpha activity
  - 1.0 Bq/litre for gross beta activity
- Values considered to be sufficiently precautionary.
- Will pick up radon daughters that can be important contributors to ingestion doses.
- Vast majority of supplies easily meet the screening values.
Monitoring programmes

- Criteria for monitoring taking into account local conditions.
  - New water supplies vs. existing supplies
  - Are measured concentrations consistently below screening levels?
  - Are there sources of potential radionuclide contamination nearby? Are they expected to be changing rapidly with time?

- Taking into account available resources and potential risks, graded approach to sampling frequency commensurate with
  - the size of the population served
  - the expected variability of radionuclide concentrations
  - the availability and results of historical monitoring records
Guidance Values

- Activity concentrations in individual radionuclides in drinking-water that would lead to 0.1 mSv/year (IDC)

- Consider all radionuclides that could contribute to dose

- IDC of 0.1 mSv/year represents a very low level of risk and is equivalent to cancer risk of $5.5 \times 10^{-6}$ which compares with carcinogenic chemicals.

- Exceeding the IDC of 0.1 mSv/y **DOES NOT** mean that the drinking-water is unsuitable for drinking. However, further investigation is required.
Table 9.2  Guidance levels for common\textsuperscript{a} natural and artificial radionuclides for members of the public

<table>
<thead>
<tr>
<th>Category</th>
<th>Dose coefficient (Sv/Bq)</th>
<th>Guidance level (Bq/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Naturally occurring radioactive decay series of uranium decay series</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uranium-238</td>
<td>$4.5 \times 10^{-8}$</td>
<td>10</td>
</tr>
<tr>
<td>Naturally occurring radioactive isotope that starts the uranium decay series</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thorium-230</td>
<td>$2.1 \times 10^{-7}$</td>
<td>1</td>
</tr>
<tr>
<td>Radium-226</td>
<td>$2.8 \times 10^{-7}$</td>
<td>1</td>
</tr>
<tr>
<td>Lead-210</td>
<td>$6.9 \times 10^{-7}$</td>
<td>0.1</td>
</tr>
<tr>
<td>Polonium-210</td>
<td>$1.2 \times 10^{-6}$</td>
<td>0.1</td>
</tr>
<tr>
<td>Naturally occurring radioactive isotope that starts the thorium decay series</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thorium-232</td>
<td>$2.3 \times 10^{-7}$</td>
<td>1</td>
</tr>
<tr>
<td>Naturally occurring radioactive isotopes belonging to the thorium decay series</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radium-228</td>
<td>$6.9 \times 10^{-7}$</td>
<td>0.1</td>
</tr>
<tr>
<td>Thorium-228</td>
<td>$7.2 \times 10^{-8}$</td>
<td>1</td>
</tr>
</tbody>
</table>

\textsuperscript{a} WHO Guidelines for drinking-water quality provide guidance values for a number of radionuclides.
Implementation of DWQ guidance values

- Both the screening levels and guidance levels (GLs) are highly conservative. Although the majority of water supplies comply with them, occasionally, guidance levels might be consistently exceeded (one RN or a combination of RNs)

- National authorities will make a decision regarding the need to implement remedial measures or to place some restriction. One key consideration is the extent to which the GLs are exceeded.
Determine gross alpha and gross beta activity

Screening values
0.5 Bq/l for gross alpha activity
1 Bq/l for gross beta activity

Are screening values exceeded?

Check validity of measurements obtained and collect further samples

Are screening values still being exceeded?

Subtract the contribution of K-40 (beta) following a separate determination of total potassium

Are screening values still being exceeded?

Look at available information on potential sources of radionuclides and develop a specific analytical strategy

Are any of the guidance levels exceeded and/or does the sum exceed unity?

Consider and, when justified, take remedial actions to reduce dose

No intervention needed, water suitable (continue sampling as normal)

Figure 9.2 Application of screening and guidance levels for radionuclides in drinking-water
For example: uranium

- Natural uranium induces nephrotoxicity, which has a lower threshold than radiotoxicity. Therefore, guideline value based on chemical toxicity.

- Original guideline value of 15 µg/litre based on laboratory animal data but increased to 30 µg/litre in the fourth edition based on more recent human data. May be very conservative but still uncertainties.

- To detect radioactivity by gross screening need >100 µg/l so 30 µg/litre is also protective of radioactivity.
WHO Guidelines for drinking-water quality do not provide a guidance value for radon.
**Radon in water**

- High radon concentrations may be found in groundwater supplies but seldom in surface drinking-water supplies
  - Surface water - No problem with $^{222}\text{Rn}$
  - Groundwater
    - Dug wells in soil aquifer – minor problem with $^{222}\text{Rn}$
    - Drilled wells in bedrocks - High to very high $^{222}\text{Rn}$ concentrations can be encountered in uranium-rich bedrock

- Straightforward and effective techniques exist to reduce the concentration of radon in drinking-water supplies
Radon in drinking-water

- **Radon** dissolved in water can be released and contribute to increase radon concentration in indoor air.
  - The % of radon that is released from water in the home varies depending on local conditions, and will occur only while the water is being discharged through the tap or shower.
  - Rule of thumb: 1000 Bq/l in water can give rise to 100 Bq/m³ in indoor air.

- Although ingested radon may deliver a radiation dose to the lining of stomach, the main route of entry into the body is via inhalation.
  - > 90% radon dose from inhalation rather than ingestion [UNSCEAR, 2000]
Managing radon in drinking water

- WHO Guidelines for drinking-water quality do not provide a guidance value for radon.

- Taking into account that human exposure from radon in water is mostly received from inhalation, it is more appropriate to measure/manage the radon concentration in indoor air rather than in drinking-water.
Health Effects of Naturally Radioactive Water Ingestion: The Need for Enhanced Studies

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1Service de Radiobiologie et Epidémiologie, and 2Service d’Etudes et Expertise en Radioprotection, Institut de Radioprotection et de Sûreté Nucléaire, Fontenay-aux-Roses, France

BACKGROUND: Radiological pollution is a potentially important aspect of water quality. However, relatively few studies have been conducted to document its possible health effects.

OBJECTIVE: In this commentary we discuss available epidemiological findings and related data from experimental studies concerning the health effects of naturally radioactive water ingestion.

DISCUSSION: Despite modest epidemiological evidence of uranium nephrotoxicity and radium effects on bone, available data are not sufficient to quantify the health effects of naturally occurring radionuclides in water. Methodological limitations (exposure measurement methods, control for confounding, sample size) affect most studies. Power calculations should be conducted before launching new epidemiological studies focusing on late pathological outcomes. Studies based on biomarkers of exposure and adverse effects may be helpful but should involve more specific molecules than biomarkers used in previous studies. Experimental data on ingestion of drinking water are limited to uranium studies, and there is some disagreement between these studies about the nephrotoxicity threshold.

CONCLUSION: Further experimental and enhanced epidemiological studies should help to reduce uncertainties resulting from dose estimation to dose–response characterization.

### Review of epidemiological studies on possible effects of natural radionuclides in DW (I)

**Table 1. Available epidemiological studies on the possible effects of naturally occurring radionuclides in drinking water.**

<table>
<thead>
<tr>
<th>Study</th>
<th>Design</th>
<th>Radionuclide</th>
<th>Average concentration in water</th>
<th>Outcome</th>
<th>No. of subjects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mao et al. 1995*</td>
<td>Cross-sectional</td>
<td>U</td>
<td>19.6 µg/L</td>
<td>Biomarkers of renal (glomerular) damage</td>
<td>140 cases</td>
</tr>
<tr>
<td>Zamora et al. 1998*</td>
<td>Cross-sectional</td>
<td>U</td>
<td>100 µg/L</td>
<td>Biomarkers of renal (tubular) damage</td>
<td>50 cases</td>
</tr>
<tr>
<td>Kurtio et al. 2002*</td>
<td>Cross-sectional</td>
<td>U</td>
<td>131 µg/L</td>
<td>Biomarkers of renal (tubular) damage</td>
<td>325 cases</td>
</tr>
<tr>
<td>Kurtio et al. 2005*</td>
<td>Cross-sectional</td>
<td>U</td>
<td>124 µg/L</td>
<td>Biomarkers of renal (tubular) damage</td>
<td>268 cases</td>
</tr>
<tr>
<td>Kurtio et al. 2006a</td>
<td>Cross-sectional</td>
<td>U</td>
<td>25 µg/L</td>
<td>Biomarkers of renal (tubular) damage</td>
<td>193 cases</td>
</tr>
<tr>
<td>Selden et al. 2009*</td>
<td>Cross-sectional</td>
<td>U</td>
<td>180 µg/L</td>
<td>Biomarkers of renal (tubular) damage</td>
<td>454 cases</td>
</tr>
<tr>
<td>Zamora et al. 2009*</td>
<td>Cross-sectional</td>
<td>U</td>
<td>88 µg/L</td>
<td>Biomarkers of renal (tubular) damage</td>
<td>54 cases</td>
</tr>
<tr>
<td>Petersen et al. 1966*</td>
<td>Ecological</td>
<td>$^{226}$Ra</td>
<td>170 mBq/L</td>
<td>Bone cancer mortality</td>
<td>267 cases</td>
</tr>
<tr>
<td>Bean et al. 1982*</td>
<td>Ecological</td>
<td>$^{226}$Ra</td>
<td>&gt;110 mBq/L</td>
<td>Cancer incidence</td>
<td>1,596 cases</td>
</tr>
<tr>
<td>Lyman et al. 1995*</td>
<td>Ecological</td>
<td>$^{226}$Ra</td>
<td>&gt;165 mBq/L</td>
<td>Leukemia incidence and mortality</td>
<td>873 incident/690 mortality cases</td>
</tr>
<tr>
<td>Fuortes et al. 1990*</td>
<td>Ecological</td>
<td>$^{226}$Ra</td>
<td>NR</td>
<td>Leukemia incidence</td>
<td>700 cases</td>
</tr>
<tr>
<td>Hess et al. 1993</td>
<td>Ecological</td>
<td>$^{226}$Ra</td>
<td>NR</td>
<td>Cancer incidence</td>
<td>33,928 cases</td>
</tr>
<tr>
<td>Collman et al. 1988</td>
<td>Ecological</td>
<td>$^{222}$Rn</td>
<td>NR</td>
<td>Cancer mortality</td>
<td>Total cancer cases NR (1,758 leukeimias)</td>
</tr>
<tr>
<td>Collman et al. 1991*</td>
<td>Ecological</td>
<td>$^{222}$Rn</td>
<td>NR</td>
<td>Cancer mortality</td>
<td>2,706 cases (1,194 leukeimias)</td>
</tr>
<tr>
<td>Kjellberg and Wiseman 1995*</td>
<td>Ecological</td>
<td>$^{222}$Rn</td>
<td>NR</td>
<td>Stomach cancer incidence and mortality</td>
<td>NR</td>
</tr>
<tr>
<td>Cech et al. 2007*</td>
<td>Ecological</td>
<td>$^{226}$Ra</td>
<td>&gt;110 mBq/L</td>
<td>Orofacial cleft defect births</td>
<td>167 cases</td>
</tr>
<tr>
<td>Cech et al. 2008*</td>
<td>Ecological</td>
<td>$^{226}$Ra</td>
<td>&gt;110 mBq/L</td>
<td>Orofacial cleft defect births</td>
<td>300 cases</td>
</tr>
</tbody>
</table>

# Review of epidemiological studies on possible effects of natural radionuclides in DW (II)

<table>
<thead>
<tr>
<th>Study</th>
<th>Design</th>
<th>Radionuclide</th>
<th>Average concentration in water</th>
<th>Outcome</th>
<th>No. of subjects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moss et al. 1995</td>
<td>Case–control</td>
<td>Gross α</td>
<td>300 mBq/L</td>
<td>Osteosarcoma incidence</td>
<td>167 cases/969 controls with other cancers, matched on age, sex, and race</td>
</tr>
<tr>
<td>Guse et al. 2002</td>
<td>Case–control</td>
<td>$^{228}$Ra + $^{226}$Ra</td>
<td>NR</td>
<td>Osteosarcoma incidence</td>
<td>319 osteosarcoma cases/3,198 general population controls matched on age, sex, and ZIP code</td>
</tr>
<tr>
<td>Finkelstein 1994*</td>
<td>Case–control</td>
<td>$^{226}$Ra</td>
<td>26 mBq/L</td>
<td>Bone cancer mortality</td>
<td>283 cases/265 controls (died of any other disease) matched on age, sex, and year of death</td>
</tr>
<tr>
<td>Finkelstein and Kreiger 1996*</td>
<td>Case–control</td>
<td>$^{226}$Ra</td>
<td>26 mBq/L</td>
<td>Bone sarcoma incidence and mortality</td>
<td>583 cases/754 controls with (or died of) any other disease matched on age, sex, and year of death or diagnosis</td>
</tr>
<tr>
<td>Hirunwathanakul et al. 2006*</td>
<td>Case–control</td>
<td>$^{228}$Ra</td>
<td>NR</td>
<td>Digestive cancer incidence</td>
<td>32 cases/136 randomly selected healthy controls</td>
</tr>
<tr>
<td>Witmans et al. 2008*</td>
<td>Case–control</td>
<td>U</td>
<td>$\approx 1$ μg/L</td>
<td>Non-Hodgkin lymphoma incidence</td>
<td>88 cases/132 controls matched on age and sex</td>
</tr>
<tr>
<td>Seiler 2004</td>
<td>Case–control</td>
<td>U</td>
<td>$\approx 2$ g/L</td>
<td>Leukemia incidence</td>
<td>16 wells as cases/100 other community wells as controls</td>
</tr>
<tr>
<td>Auvinen et al. 2002</td>
<td>Case–cohort</td>
<td>U</td>
<td>0.45 Bq/L</td>
<td>Leukemia incidence</td>
<td>35 cases/274 controls matched on age and sex</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$^{228}$Ra</td>
<td>30 mBq/L</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$^{222}$Rn</td>
<td>500 Bq/L</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Auvinen et al. 2005</td>
<td>Case–cohort</td>
<td>U</td>
<td>0.45 Bq/L</td>
<td>Stomach cancer incidence</td>
<td>107 cases/371 controls matched on age and sex</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$^{228}$Ra</td>
<td>30 mBq/L</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$^{222}$Rn</td>
<td>500 Bq/L</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kurtio et al. 2006b</td>
<td>Case–cohort</td>
<td>U</td>
<td>0.45 Bq/L</td>
<td>Urinary cancer incidence</td>
<td>112 cases (61 bladder, 51 kidney)/274 controls matched on age and sex</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$^{228}$Ra</td>
<td>30 mBq/L</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>$^{222}$Rn</td>
<td>500 Bq/L</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

NR, not reported.

*Statistically significant increase in the health damage of interest.
Experimental studies about health risks

Animal and in-vitro studies

- Uranium
  - Biological effects on kidney and bone
- Radium
  - Effects on bone sarcomas ($^{228}$ Ra) and head and neck sarcomas ($^{226}$ Ra)
- Radon
  - Very few experimental studies, uncertainties on internal dose assessment (transit time through gastrointestinal tract and whole-body radon retention)
What are the health risks from radionuclides in drinking water?

- Neither epidemiological studies nor experimental data are informative enough to quantify the health effects resulting from exposure to naturally-occurring radionuclides, including radon, in water.

- In addition, no experimental studies were performed on cancer in animals following an oral exposure to radon and its progeny.
Perception and Trust

- There is usually little choice in drinking-water.

- Providing alternative sources can be logistically very difficult and affects subsequent actions.

- If a decision to issue a ‘Do Not Drink’ order then need to have clear basis for withdrawal of the order

- Important because it may drive consumers to more “acceptable” but less safe water sources

- Measurements/dose assessments need to be correct and appropriate for the situation
Key take home message

Screening levels and guidance levels are conservative and should not be interpreted as mandatory limits. Exceeding a guidance level should be taken as a trigger for further investigation, but not necessarily as an indication that the drinking-water is unsafe.
Thank you very much!
Additional/supporting information
Examples of the efficacy of different water treatment processes are provided

<table>
<thead>
<tr>
<th>Element</th>
<th>Coagulation</th>
<th>Sand filtration</th>
<th>Activated carbon</th>
<th>Precipitation softening</th>
<th>Ion exchange</th>
<th>Reverse osmosis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strontium</td>
<td>xx</td>
<td>xx</td>
<td>x</td>
<td>xxxxxx</td>
<td>xxx</td>
<td>xxxx</td>
</tr>
<tr>
<td>Iodine</td>
<td>xx</td>
<td>xx</td>
<td>xxx</td>
<td>x</td>
<td>xxx</td>
<td>xxxx</td>
</tr>
<tr>
<td>Caesium</td>
<td>xx</td>
<td>xx</td>
<td>x</td>
<td>xx</td>
<td>xxx</td>
<td>xxxx</td>
</tr>
<tr>
<td>Radium</td>
<td>xx</td>
<td>xxx</td>
<td>xx</td>
<td>xxxxxx</td>
<td>xxx</td>
<td>xxxx</td>
</tr>
<tr>
<td>Uranium</td>
<td>xxxxxx</td>
<td>x</td>
<td>xx</td>
<td>xxxxxx</td>
<td>xxx</td>
<td>xxxx</td>
</tr>
<tr>
<td>Plutonium</td>
<td>xxxxxx</td>
<td>xx</td>
<td>xxx</td>
<td>x</td>
<td>xxx</td>
<td>xxxx</td>
</tr>
<tr>
<td>Americium</td>
<td>xxxxxx</td>
<td>xx</td>
<td>xxx</td>
<td>x</td>
<td>xxx</td>
<td>xxxx</td>
</tr>
<tr>
<td>Tritium</td>
<td>Not possible to remove (some removal by aeration of water, not quantified)</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

\(^a\) x = 0–10% removal; xx = 10–40% removal; xxx = 40–70% removal; xxxxx = > 70% removal.
Examples of methods for measurement of specific radionuclides and references are provided.

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Analytical method</th>
<th>Volume (l)</th>
<th>Detection limit (mBq l⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross α</td>
<td>Phosphate precipitation, liquid scintillation counting</td>
<td>0.3</td>
<td>20</td>
</tr>
<tr>
<td>Uranium 238U, 234U, 235U</td>
<td>Kinetic phosphorescence analysis</td>
<td>0.02</td>
<td>0.7</td>
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<tr>
<td>228Ra</td>
<td>Co-precipitation with barium sulphate and transfer into carbonate, extraction chromatography, low-level beta counting (228 Ac)</td>
<td>0.3</td>
<td>5–10</td>
</tr>
<tr>
<td>226Ra</td>
<td>Co-precipitation with barium sulphate, emanation, gross alpha-counting (radon and daughters, scintillation chamber)</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>210Pb, 210Po</td>
<td>Spontaneous deposition (Bi and Po) on Ni-disks, low-level beta counting (210 Bi), alpha counting (210 Po)</td>
<td>4.0</td>
<td>2.0</td>
</tr>
<tr>
<td>222Rn</td>
<td>Liquid scintillation counting</td>
<td>0.015</td>
<td>1000</td>
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