centre of expertise for waters

Radon in groundwater drinking water supplies in Scotland

Published by CREW – Scotland's Centre of Expertise for Waters. CREW connects research and policy, delivering objective and robust research and expert opinion to support the development and implementation of water policy in Scotland. CREW is a partnership between the James Hutton Institute and all Scottish Higher Education Institutes supported by MASTS. The Centre is funded by the Scottish Government.

This document was produced by:
Name: Ioanna Akoumianaki[1], Jackie Potts[2], Adenkule Ibiyemi[1], Sue Morris[1]

1. James Hutton Institute,
   Craigiebuckler, Scotland UK
   AB15 8QH.

2. Biomathematics and Statistics Scotland
   JCMB, The King's Buildings,
   Peter Guthrie Tait Road,
   EDINBURGH, EH9 3FD,
   Scotland, UK.

Please reference this report as follows: Ioanna Akoumianaki, Jackie Potts, Adenkule Ibiyemi, Sue Morris (2015) Radon in groundwater drinking water supplies in Scotland **(**R203035-00).
Available online at: crew.ac.uk/publications

Cover photograph courtesy of: <CREW >

Contents

centre of expertise for waters

Acknowledgements
We wish to thank the Drinking Water Quality Regulator and Scottish Water for their help in designing representative surveys and for providing the results of radon analyses in groundwater public and private water supplies.

Glossary

Absorbed Dose is the quantity of energy imparted to unit mass of matter (such as tissue) by Ionising Radiation.

Becquerel (Bq) is the SI unit for Activity and is equivalent to 1 disintegration per second (dps).

Effective dose is obtained by taking the Equivalent Dose and multiplying by a Tissue Weighting Factor which relates to the organs / tissues under consideration. The quantity can be used to express Detriment to the whole body as a summation of several different doses of radiation with varying radiation weighting factors (radiation type) and targets.

Equivalent Dose is a quantity which takes into effect 'radiation quality', which relates to the degree to which a type of Ionising Radiation will produce Detriment.

Half-life represents the time taken for half the Atoms in a Radioactive substance to undergo decay and change into another nuclear form (either a radioactive daughter product or a stable form). It is therefore the time taken for the Activity of a radioactive sample to decay by half.

Indicative dose or 'ID' means the committed effective dose for one year of ingestion resulting from all the radionuclides whose presence has been detected in a supply of water intended for human consumption, of natural and artificial origin, but excluding tritium, potassium-40, radon and short-lived radon decay products [1].

Ionising radiation: According to the Ionising Radiations Regulations 1999, UK (http://www.legislation.gov.uk/uksi/1999/3232/contents/made) it 'means transfer of energy in the form of particles or electromagnetic waves of a wavelength of 100 nanometers or less or a frequency of 3×10^{15} hertz or more capable of producing ions directly or indirectly'.

Parametric value means the value of radioactive substances in water intended for human consumption above which Member States shall assess whether the presence of radio-active substances in water intended for human consumption poses a risk to human health which requires action and, where necessary, shall take remedial action to improve the quality of water to a level which complies with the requirements for the protection of human health from a radiation protection point of view [1].

Radioactive decay describes the process where by Radioactive substances decay spontaneously with the release of energy in the form of Electromagnetic Radiation or particulate radiation. The rate of radioactive decay will depend on the Half-Life.

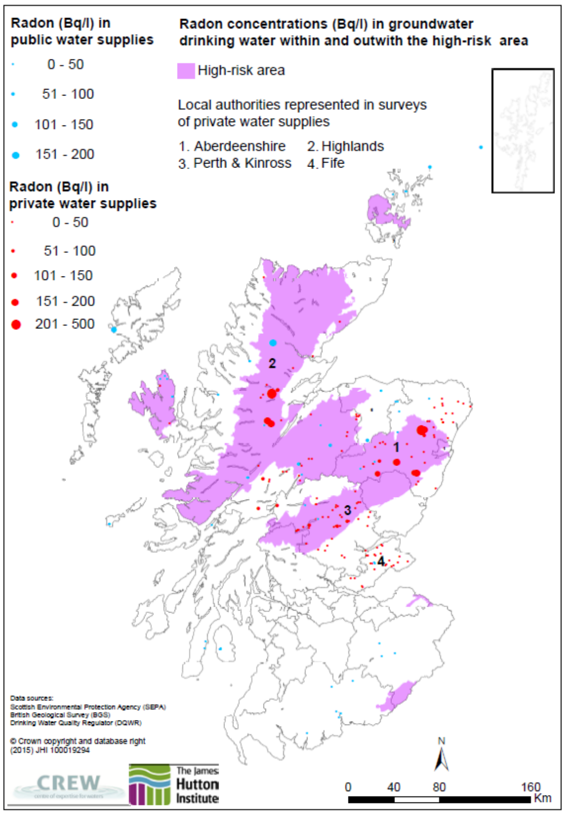
Sievert (Sv) is the SI unit of Equivalent Dose & Effective dose . The equivalent older unit is the Rem where 1Sv = 100 rem.

Executive Summary

Are radon concentrations higher in the high-risk area, where the underlying geology is likely to deliver high radon concentrations in groundwater and indoor air, than elsewhere in Scotland? What should the minimum allowable radon concentration in drinking water be to protect public health? What is the evidence from representative surveys in public and type A private groundwater drinking water supplies on radon concentrations? This report addresses these questions to help inform the transposition of the Council Directive 2013/51/Euratom into Scots law for regulating radon in drinking water.

Main findings from representative surveys:

- Overall, radon concentrations are significantly higher within than outwith the high-risk area. Radon concentrations between 100 and 500 Bq/l are found in Aberdeenshire, specifically in granite-rich areas, in the wider area of the Highlands, and in the Outer Hebrides.
- Radon concentrations in the groundwater supplies surveyed range between
  - 10 Bq/l and 494 Bq/l within the high-risk area, with highest values in private supplies
  - 10 Bq/l - 123 Bq/l outwith the high-risk area, with highest values in public supplies.



- The implications of the higher radon values found in the high-risk area (100-497 Bq/l) are
  - An increase of the radon emanating from tap-water into indoor air by 10-50 Bq/m^3.
  - An annual indicative dose by ingestion of 0.18 - 0.9 mSv; this is within the range of radiation from exposure to radon in drinking water in the UK (i.e. 0.01 – 1 mSv/year).
  - The highest radon concentration (i.e. 497 Bq/l) corresponds to an annual total indicative dose by both ingestion and inhalation of about 2.14 mSv; this is lower than the total average radiation dose received by an individual in the UK, i.e. 2.5 mSv/yr, but higher than the average dose due to total radon in the UK, i.e. 1.3 mSv/yr.

- In terms of protection and mitigation, it would be more effective to adopt a holistic approach to mitigation of radon in water and indoor air within the high-risk area rather than focus on removing radon from the least hazardous source, i.e. water.

- Overall, the general population in Scotland is not chronically exposed to high radon in water:
    - Representative surveys focused on the source (point-of-entry), therefore radon in tap-water may be lower or can be mitigated with point-of-entry treatment.
    - Type A private groundwater supplies in the high-risk area found to have radon above 100 Bq/l are supplied as part of commercial or public activity (i.e. holiday lets, B&Bs) where exposure is usually of a short term nature.
    - The range of radon in groundwater in the high-risk area is within the lower range of radon values in water in granite-rich and sandstone areas elsewhere in the world.

Background

The Directive requires that Member States specify a Parametric Value for radon in drinking water between 100 and 1000 Bq/l and a radon Action Level at 1000 Bq/l. Monitoring is necessary only where representative surveys show the specified Parametric Value might be exceeded; minimum monitoring frequency depends on volume of water consumed (i.e. 1 to 2 samples a year for type A private water supplies and up to monthly for larger public groundwater supplies). Radon can present a health hazard when tap-water is freshly drawn from radon-rich groundwater supplies and radon emanates into poorly ventilated indoor spaces. An earlier CREW project identified **a high-risk area comprising groundwater waterbodies underlying areas with 10% of homes at risk of exceeding the Action Level for radon in indoor air (200 Bq/m^3)** set by the Health Protection Agency.

Research approach

In Scotland, 77 public and 1497 type A private water supplies take water from groundwater sources. Representative surveys at the treatment works of all public groundwater supplies and at the source of 154 type A private groundwater within and outwith the high-risk area serving 1272 properties explored the effect of underlying geology on groundwater radon. Radon was sampled and analysed by trained Scottish Water staff. Statistical tests (Mann-Witney) helped compare radon concentrations within and outwith the high-risk area.

Recommendations for radon in drinking groundwater supplies

- Parametric Value and Action Level should be between 100 and 500 Bq/l to ensure protection against health hazards from exposure to radon in water.
- Public groundwater supplies should be monitored when residence time of water in treatment plants is shorter than radon's half-life (i.e. 3.8 days). Mitigation and monitoring may target treatment works provided there is no adverse change in the concentration value between the sampling point and tap-water.
- Type A private groundwater supplies (wells, boreholes, or springs) should be monitored within the high-risk area to ensure compliance with the Parametric Value and Action Level.
    - Monitoring should target tap-water but mitigation should target points-of-entry;
    - Awareness, mitigation advice, and monitoring should be planned by Local Authorities but mitigation may be the supply owner's responsibility.

- Synergies could be developed with the existing Scottish Government programme for radon in indoor air to enable a holistic approach to radon awareness and mitigation in all properties, including those served by type B private groundwater supplies within the high-risk area.

1. Need for evidence to inform regulations for radon in drinking water

As part of an on-going review of the implications of the Council Directive 2013/51/Euratom [1] on radon regulations in drinking water, Scotland's Centre of Expertise for Waters (CREW) mapped areas of likely low, medium, and high exposure to radon in groundwater. The map uses geological data from the British Geological Survey (BGS) to indicate 'what earth delivers' for radon. The high-risk area comprises groundwater waterbodies underlying extensive parts of the Highlands, Aberdeenshire, and the Orkney Islands; smaller areas in Perthshire, Angus, Moray, and Stirling; and a few spots in East Lothian and the Scottish Borders. The high-risk area includes all areas with high radon potential, i.e. areas with 10% of homes at risk of exceeding the Action Level for radon concentrations in indoor air (200 Bq/m^3) set by the Health Protection Agency. This approach accounts for the radioactivity of rock or soil and the health risks from radon and its decay products, but it needs validation with representative surveys in groundwater public and private water supplies.

Radon regulations must be transposed to Scots law by November 2015. This report examines radon concentrations from groundwater drinking water supplies within and outwith the high-risk area to inform decisions on:

- A radon target in drinking water, an exceedence of which should trigger investigation(i.e. Parametric Value).
- An Action Level above which remedial action is required.
- Monitoring sites to capture likely exceedances of the Parametric Value and Action Level and ensure effective protection of the population from exposure to radon.

2. Why and when is radon a problem in drinking water?

Radon (radon-222) is a naturally occurring, water-soluble, geogenic gas produced by the radioactive decay of uranium-bearing rock formations. It has a half-life of 3.8 days, and once released in air, it decays to short-lived radioactive solid particles (radon progeny) including polonium, lead, and bismuth. Breathing radon in the indoor air of homes is the primary public health risk from radon, which is the second leading cause of lung cancer in the general population in the UK and worldwide. Radon in drinking water is the cause of about 89% of lung cancers resulting from breathing radon released from water, and of 11% of stomach cancers resulting from radon in drinking water [2].

Waterborne radon can present a health hazard when water is freshly drawn from radon-contaminated groundwater supplies. Public water supplies come to households via large storage systems, often with long residence times. This should allow for any radon originally present in drinking surface water or groundwater supplies to be released into the air or to decay to low levels before reaching the consumer. In properties served by groundwater private supplies and small public waterworks, especially those in areas underlain by uranium-bearing bedrock, the time between the pumping and consumption of tap-water may be well within radon's half-life. In these cases, the major routes of exposure to radon are by:

(i) Ingestion before radon degassing from tap-water to the indoor air.
(ii) Inhalation of the radon gas emanating from tap-water into the indoor air; the ratio of radon in water (Bq/l) to that in air (generated from the water) (Bq/m^3), also known as the transfer coefficient of radon from water to air, is about 10^{-4}, i.e. for every 1 Bq/l of radon in tap-water there is an increase by 0.1 Bq/m^3 of radon in indoor air.
(iii) Inhalation of the solid particles of the radon progeny that may cling to indoor air dust.

3. What is the best approach to regulating radon in groundwater?

The Directive requires that Member States specify a parametric value for radon in drinking water between 100 and 1000 Bq/l and an Action Level at 1000 Bq/l. Monitoring is required only where evidence shows the specified Parametric Value might be exceeded.

In Scotland, the 77 (i.e. 17%) public and 1497 (i.e. about 64%) type A private water supplies take water from groundwater sources, but only 24 public and 453 private groundwater supplies are located within the high-risk area. Representative surveys explored the effect of underlying geology on groundwater radon in public and private water supplies within and outwith the high-risk area to provide evidence for the range of radon in drinking water in Scotland. The surveys included all public groundwater supplies, and 154 randomly selected private water supplies (i.e. 53 boreholes, 88 springs, 13 wells) from all supplies serving premises occupied most of the time in the Highlands, Aberdeenshire, Perth and Kinross, and Fife. Of the selected supplies, 101 were within the high-risk area, and 53 outwith the high-risk area. Radon was sampled at public water treatment plants, and at the source of private water supplies located in Aberdeenshire, Highlands, Perth and Kinross, and Fife. Appendix 1 describes the design of representative surveys.

If the surveys show that radon is significantly higher within than outwith the high-risk area, then regulations must ensure that a Parametric Value between 100 and 1000 Bq/l is an achievable target for:

- Monitoring all areas of likely exposure to radon to identify any exceedances of regulations.
- Mitigating radon in water above the Parametric Value and Action Level after abstraction and before consumption to achieve compliance with regulations.
- Aligning with the Scottish Government programme for awareness, mitigation, and protection from radon in indoor air[1] aimed at locations where more than 5% of homes have radon in indoor air at or above the Action Level (200 Bq/m^3). **This is to address that the annual indicative dose from exposure to 200 Bq/m^3 of radon in indoor air equals the annual dose from exposure to 1000 Bq/l of radon in water** (see Appendix 2 for these estimates).

If radon concentrations are below 100 Bq/l within and outwith the high-risk area, then monitoring is not necessary according to the Directive's provisions. But if radon concentrations in groundwater are above 100 Bq/l, then more sampling is necessary to identify a fit-for-purpose Parametric Value and monitoring.

4. Radon concentrations within and outwith the high-risk area

Findings show:

- Overall, radon concentrations are significantly higher within than outwith the high-risk area.
- Radon values above 100 Bq/l are found in Aberdeenshire, specifically in granite-rich areas, in the wider area of the Highlands, and in the Outer Hebrides. This indicates exceedances of the lower threshold for a Parametric Value set by the Directive.
- Radon values in Scotland range from (Figure 1):
    - below 10 Bq/l up to 494 Bq/l within the high-risk area; and

[1] In response to the publication of the radon potential map, the Scottish Government has launched an awareness campaign and announced free testing for homeowners in areas with a 5% or more chance of houses being above the Action Level for indoor air radon. This policy includes all homes within the high-risk area for radon in groundwater. (https://www.gov.uk/government/publications/radon-targeted-survey-of-scottish-homes)

- below 10 Bq/l up to 123 Bq/l outwith the high-risk area.

- Radon concentrations in public groundwater supplies range (Figure 1):
  - from below 10 Bq/l up to 197 Bq/l in the high-risk area; and
  - from below 10 Bq/l up to 123 Bq/l outwith the high-risk area.
- About 30% of public groundwater supplies located in the high-risk area display radon concentrations below 10 Bq/l.
- About 50% of all public groundwater supplies display radon values between 50 and 100 Bq/l.
- About 9% of all the public groundwater supplies display radon levels at or above 100 Bq/l.
- Radon concentrations in private groundwater supplies range from (Figure 1):
  - below 10 Bq/l up to 494 Bq/l within the high-risk area
  - below 10 Bq/l up to 75 Bq/l outwith the high-risk area.

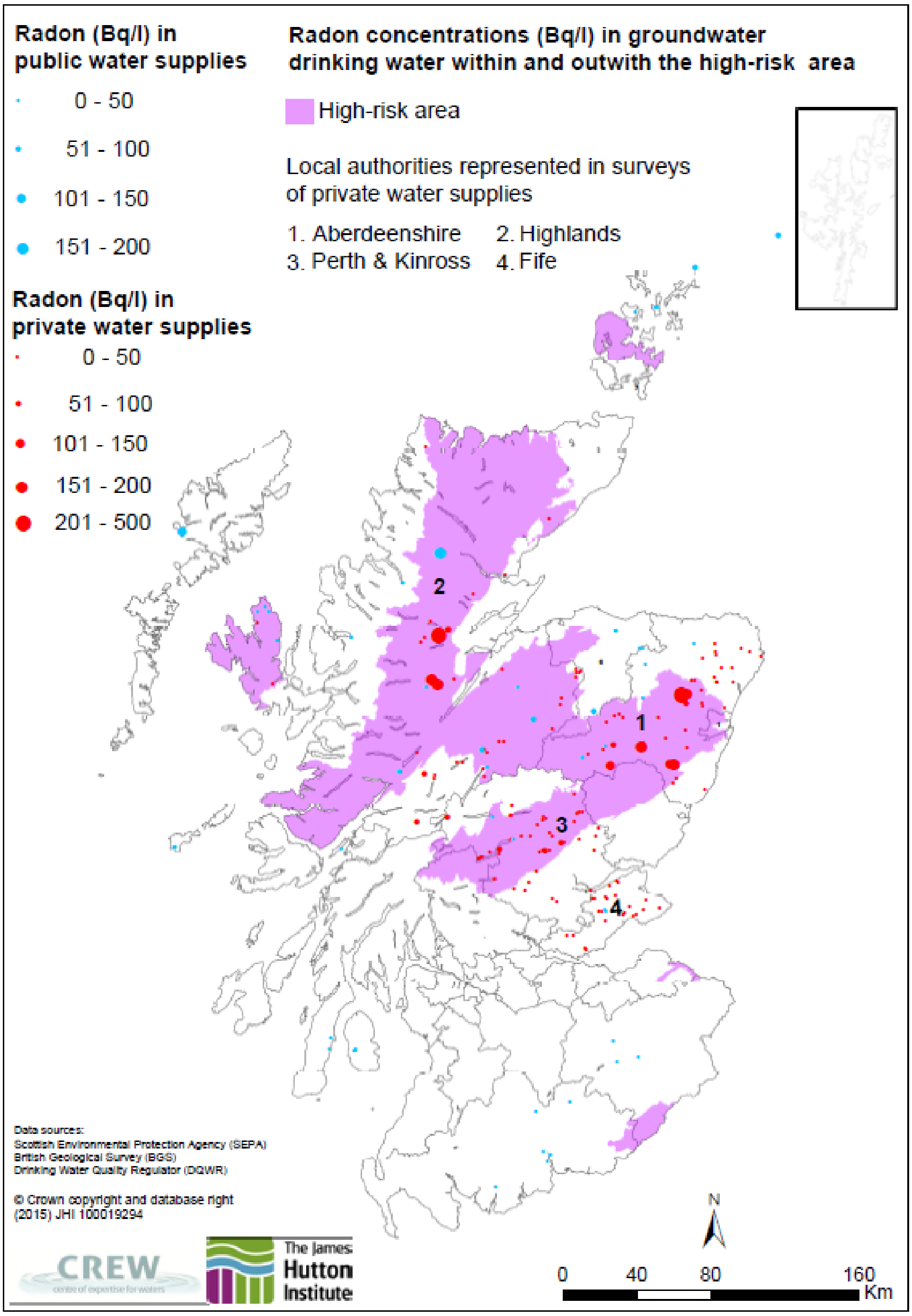


Figure 1. Radon concentrations in public and private groundwater drinking water supplies within and outwith the high-risk area.

- In 13% of the private water supplies surveyed, radon exceeds 100 Bq/l, all of exceedances found in springs and boreholes.
- Only in 2% of the private water supplies surveyed do radon values exceed 200 Bq/l.
- Differences between the high-risk area and the area outwith are not significant at a local authority level; all the values above 100 Bq/l are found in Aberdeenshire and the Highlands.
- Overall, radon concentrations exceeding 123 Bq/l are clearly found only in the high-risk area.
- The range of radon values in Aberdeenshire and the Highlands demonstrated here are higher than the tap-water radon concentrations from wells (type-B private water supplies) located in granite-rich and red sandstone areas in Scotland (i.e. Aberdeenshire, the Highlands, the Orkney Islands, and Dumfries and Galloway) found in previous studies (Appendix 3). This may be because radon undergoes natural degassing and decay between abstraction points and tap-water.
- In about 50% of the private water supplies surveyed radon concentrations are below 10 Bq/l.
- Monitoring for radon in water in type A private water supplies within the high-risk area and analysis of 20 samples a week is feasible.
- The range of radon concentrations in the high-risk area in Scotland is within the lower range of values found in granite-rich and sandstone areas elsewhere in the world (Table 1).

Table 1. Geological controls on radon concentrations in drinking water.

Underlying Geology	Radon in water (Bq/l)	Reference
Scotland (high-risk area): Private supplies	<10 – 494	Present study
Scotland (high-risk area): Public supplies	<10 - 123	
Surface freshwater	<4	[3]
Springs	50 – 740	[4, 5]
Wells dug in soil	Normal: 10-300	[3]
	Granite: 40-400	[6]
Wells in sedimentary rock	10-150	[3]
Wells in crystalline rock	U-poor: 50-500	[3]
	U-rich granites 300-4,000 (max=63,000)	[7]
Wells in granite bedrock	10-42,000	[6, 8]
Boreholes in granite bedrock	Max=80,000	[8]
Public water supplies in granite-rich areas	Max=1630	[8]

- The higher radon concentrations in private water supplies within the high-risk area (100-497 Bq/l) can increase radon in indoor air by 10-50 Bq/m^3 every time the tap is used in poorly ventilated properties, assuming radon is not mitigated between the abstraction point and tap[2]. This indicates a greater risk of exposure to radon by inhalation in areas where radon concentrations in indoor air are already high due to the underlying geology, such as in the high-risk area.
- The indicative dose (Glossary) from ingestion of groundwater from private water supplies in the high-risk area with high radon concentrations (i.e. 100-497 Bq/l) can reach up to 0.18 -

[2] Radon transfer coefficient from water to air= 10^{-4}

0.9 mSv/year (see Appendix 2 for calculations). This is within the range of radiation from exposure to radon in drinking water in the UK, i.e. 0.01 – 1 mSv/year [9, 10].

- The annual total indicative dose (mSv/year) from both ingestion and inhalation of water containing 497 Bq/l (i.e. the highest concentration in the representative surveys) is about 2.14 mSv (see Appendix 2 for calculations). This is smaller than the total annual average radiation dose received by an individual in the UK, i.e. 2.5 mSv[3], but higher than the annual average exposure due to radon from all sources in the UK, i.e. 1.3 mSv[3].
- Type A private groundwater supplies in the high-risk area found to have radon above 100 B/l are supplied as part of commercial or public activity (i.e. holidays lets, B&Bs). This demonstrates that the general population is not chronically exposed to high radon concentrations in water in Scotland.

5. Policy recommendations

The evidence collected during the representative surveys is essential for specifying regulations for radon in water in Scotland.

Identifying a Parametric Value for radon in water should address the far greater risk from exposure to radon in the indoor air. Thus, the cost of mitigating radon in water, including staff time, and maintenance of mitigating devices with the aim to achieve a low parametric value would be difficult to justify to the public. In addition, it would be more effective to adopt a holistic approach to mitigation of radon from all sources within the high-risk area rather than focus on removing radon from the least hazardous source, i.e. water. This will help communicate the hazards from the key pathway of exposure, i.e. inhalation, and ensure the engagement of local authorities and the public where exposure to radon is more likely, i.e. in the high-risk area. In this line, it is reasonable to assume that a single standard for a Parametric Value and Action Level will communicate a clear message to the public about mitigation and protection from exposure to radon.

Monitoring and mitigation are different in public and private groundwater supplies. Groundwater in public water treatment plants may be treated to ensure that radon is mitigated before it enters the distribution network. Radon mitigation in type A private water supplies may involve raising awareness of radon health hazards, and providing advice for safe mitigation practices; it may also include financial incentives for the purchase of devices removing radon at point-of-entry or tap. This approach may also cover type B private groundwater supplies within the high-risk area.

Specific recommendations and their rationale are presented below.

5.1 Monitoring

Recommendations for monitoring sites and frequencies for radon in drinking water are as follows:

- For both public and private water supplies
  - Seasonal monitoring is <u>not required</u>.
  - Monitoring is <u>not required</u> in surface water supplies.

- For public water supplies
  - Monitoring in public groundwater supplies is <u>optional</u> when the residence time of water in treatment plants is longer than radon's half-life.

[3] https://www.gov.uk/government/publications/ionising-radiation-dose-comparisons/ionising-radiation-dose-comparisons

- Monitoring in public groundwater supplies is required when the residence time of water in treatment plants is shorter than radon's half-life, e.g. in small-scale public groundwater supplies, and when no treatment is in place for removing radon from water. Monitoring may target any point 'within the supply zone or at the treatment works provided there is no adverse change in the concentration value between the sampling point and the point of compliance' as reported in the Directive. In this context, monitoring for groundwater public water supplies could be carried out at the treatment works.

- For private water supplies
  - Monitoring of type A private water supplies taking water from groundwater sources (wells, boreholes, or springs) is required within the high-risk area to ensure compliance with the Parametric Value and Action Level.
  - Local Authorities must plan for awareness and advice to both users and owners of these groundwater supplies to ensure mitigation of radon in water between source and tap.
  - Monitoring of private groundwater supplies should target points of compliance, i.e. tap-water.
  - Mitigation of radon in groundwater private water supplies is the responsibility of users and owners.
  - Replicate tap-water samples should be collected from the same distribution network of groundwater private supplies; recording the number of properties and type of supply will help assess any causes of variation in radon levels within a distribution network, and inform mitigation practice before the water reaches the tap.

5.2 Parametric Value – Action Level

Specifying a Parametric Value and Action Level between 100 and 500 Bq/l has many advantages for users of both public and private water supplies. It will:

- Target mitigation in the high-risk area, where exceedances of the Parametric Value are more likely, to ensure compliance with regulations.
- Ensure that radon in water will have a minor contribution to radon concentrations in indoor air in homes within the high risk area.
- Develop synergies in terms of mitigation and awareness with the existing Scottish Government programme for radon in indoor air; this will send cost-effectively a clear message to the users of private water supplies about the need for integrated water and indoor air radon mitigation in the high-risk area.

There are however certain limitations for a Parametric Value and Action Level for radon in water to be between 100 and 500 Bq/l including:

- Costly and difficult implementation. Ensuring compliance with the regulations involves representative sampling, analysis, and mitigation advice for the 1272 properties served by the 453 private groundwater supplies in 10 local authorities. A solution to this could be to target awareness and mitigation advice in the high-risk area, but target mitigation and monitoring in the high-risk area of the Highlands and Aberdeenshire, where exceedances are more likely.
- Insufficient protection of the population from exposure to the hazards of ionising radiation. The Environment Protection Agency in the US (USEPA) estimates that lifetime exposure to drinking water at 148 Bq/l would increase lifetime cancer risk of 26 in 10,000 to the general population, which exceeds the risk range of 10^{-6} - 10^{-4} traditionally used by USEPA in developing national drinking water standards[4]. The high-risk area in Scotland, however,

[4] water.epa.gov/lawsregs/rulesregs/sdwa/radon/upload/epa815r12002.pdf

contains commercial and public premises; therefore the risks from chronic exposure to radon in water of type A private water supplies at or above 148 Bq/l are negligible. It is not easy, however, to infer risks from chronic exposure to radon for the users of type B private groundwater supplies in the high-risk area without representative surveys for type B supplies and without knowing the residence time of water before consumption.

Specifying a Parametric Value and Action Level at 1000 Bq/l, has many disadvantages. It fails to:

- Target mitigation of radon concentrations between 300 and 500 Bq/l that may be rare but not unlikely; these values represent a radiation dose above the annual average dose of radon radiation in the UK.
- Support the existing policy of the Scottish Government that aims to ensure that radon in indoor air from all sources remains below 200 Bq/m^3 in the high-risk area.
- Protect cost-effectively the general population against the hazards of ionising radiation. A radon concentration of 1000 Bq/l in drinking-water discharged from a tap will, on average, increase the radon concentration by 100 Bq/m^3 in indoor air [8, 10, 15, 16]; such increases of radon in indoor air correspond to a rise in lung cancer risk by 10 to 16% [61, 64, 65, 66].

5.3 Mitigation in private water supplies

Radon can be removed from water either before reaching the tap or at the tap[5].

- Point-of-entry treatment removes radon from the water before it reaches the tap using:
  - granular activated carbon (GAC) filters, which are low-cost but can collect radioactivity and may require a special method of disposal; and
  - aeration devices, which bubble air through the water and carry radon gas out into the atmosphere through an exhaust fan, although these are relatively costly.
- Point-of-use treatment devices are installed on a tap or under the sink to remove radon from tap-water. These devices, however, treat only a small portion of water before needing replacement because of radon contamination; they represent the most ineffective approach to reducing the risk from breathing radon released into the air from all water used in the home (e.g. bathroom).

6. Conclusion

Representative surveys provided the evidence needed to inform DWQR of the implications for Scotland of the provisional EC regulations for radon in water. This CREW report presents radon concentrations in groundwater in Scotland, and the geological, radiological, and health protection criteria to specify a Parametric Value and Action Level for radon in drinking water and the monitoring to ensure compliance with the regulations. Recommendations specify monitoring and mitigation of radon in all groundwater public water supplies at the treatment plants, and in the high-risk area for private water supplies. CREW also recommends a common standard for Action Level and the Parametric Value between 100 and 500 Bq/l to ensure alignment with the policy for radon in indoor air implemented by the Scottish Government. These recommendations will support the transposition of the Council Directive 2013/51/Euratom into Scots law by November 2015.

[5] http://epa.gov/radon/pubs/consguid.html

Appendix 1: Design of representative sampling

Representative surveys were designed to ensure that the range of radon concentrations in groundwater public and type A supplies within and outwith the high-risk area is captured to inform decision making. No surveys were carried in type B private groundwater supplies.

The high-risk area contains only 24 out of 77 public groundwater supplies throughout Scotland and 453 out of the 1497 type A private groundwater supplies overall. Representative surveys included all public groundwater supplies, and 154 private water supplies (i.e. 53 boreholes, 88 springs, 13 wells), of which 101 are within the high-risk area and 53 outwith the high-risk area. Private water supplies served 1272 properties in the following local authorities: Aberdeenshire, Highlands, Perth and Kinross, and Fife.

Radon samples were collected and processed by trained Scottish Water staff. Laboratory analyses were carried out using gamma-spectroscopy. Private water supplies for sampling were randomly selected from a list of all supplies serving premises occupied most of the time in the Highlands, Aberdeenshire, Perth and Kinross, and Fife.

Comparisons of data between the high-risk and non-high-risk areas involved non-parametric tests (i.e. Mann-Whitney tests). Data were classified (i.e. 0-50, 51-100, 101-150, 151-200, 201-500 Bq/l) and mapped using ArcGIS.

Appendix 2. Summary of annual indicative dose (ID) values from ingestion and inhalation of waterborne radon

Various models have been developed for estimating the radiation dose to different organs and tissues from ingested radon, but estimates may differ by a factor of 3. The ID from ingestion of radon ($ID_{ingestion}$) can be calculated using the following equation[6]:

$$ID_{ingestion} = Conversion_{ingestion} \text{ X } Consumption_{tap\text{-}water} \text{ X } Radon_{tap\text{-}water} \quad \text{Eq.(1)}$$

where,

- $Conversion_{ingestion}$: conversion factor of committed effective dose from ingestion of radon in water equal to 3.5 X 10^{-8} Sv/Bq for adults [8,10] or 1.0 X 10^{-8} [11];
- $Consumption_{tap\text{-}water}$: average annual consumption of water;
- $Radon_{tap\text{-}water}$: average radon concentration in drinking water.

UNSCEAR[7] has also recommended a conversion factor for the ID from the radon emanating from tap-water and then inhaled ($ID_{inhalation}$). This can be calculated using the following equation:

$$ID_{inhalation} = Conversion_{inhalation} \text{ X } Radon_{tap\text{-}water} \text{ X } Transfer_{water\ to\ air} \text{ X } F_{radon\ to\ progeny} \text{ X } T_{indoors} \quad \text{Eq. (2)}$$

where,

- $Conversion_{inhalation}$: conversion factor of committed effective dose from inhalation of waterborne radon equal to 9 X 10^{-9} Sv/Bq;
- $Radon_{tap\text{-}water}$: annual average radon concentration in drinking water;
- $Transfer_{water\ to\ air}$: Radon transfer coefficient from tap-water to air, equal to 0.1 l/m^3 (1.0 X 10^{-4});
- $F_{radon\ to\ progeny}$: indoor radon—daughter's equilibrium factor, equal to 0.4
- $T_{indoors}$: average annual time spent indoors equal to 7,000 h.

[6] www.ilo.org/...**protect**/---.../---**safe**work/.../publicat**ion**/wcms_171036.pdf
[7] www.unscear.org/docs/reports/annexb.pdf

The ID from inhalation of indoor radon from both ground and waterborne sources ($ID_{indoor\ radon}$), can be calculated using the following equation[14]:

$$ID_{indoor\ radon} = Conversion_{inhalation} \times Radon_{indoor\ air} \times Transfer_{water\ to\ air} \times F_{radon\ to\ progeny} \times T_{indoors} \quad \text{Eq. (3)}$$

where,
$Radon_{indoor\ air}$: annual average radon concentration in indoor air;
$Conversion_{inhalation}$, $Transfer_{water\ to\ air}$, $F_{radon\ to\ progeny}$, and $T_{indoors}$ as in Eq (2).

Using Eq. (1), (2) and (3) for a range of $Radon_{tap\text{-}water}$ and $Radon_{indoor\ air}$ values, we can estimate $ID_{ingestion}$, $ID_{inhalation}$, and $ID_{indoor\ radon}$ for adults, for different scenarios of radon contamination of drinking water and indoor air, and for different regulatory frameworks (Table IIa and IIb).

For these estimations we used the following conversion equations
$Conversion_{ingestion}$=3.5 X 10^{-8} Sv/Bq
$Conversion_{inhalation}$=9 X 10^{-9} Sv/Bq.
Annual drinking water intake has been estimated for reference individuals.
The estimates are 500 l/y for adults, 350 l/y for children and 150 l/y for infants [ICRP, 1975].
However, IPCS (1994) recommends an average daily intake equal to 2 l per day .

Table IIa. Indicative dose (ID) from exposure to radon in drinking water by ingestion and inhalation.

Exposure to radon in drinking water	Radon in drinking water (Bq/l)			
	100 EU min. Parametric Value	148 US EPA Action Level	500	1000 Max. Parametric Value EU Action Level
$ID_{ingestion}$ (mSv/year)	0.18	0.3	0.88	1.8
$ID_{inhalation}$ (mSv/year)	0.25	0.4	1.25	2.5
$ID_{waterborne\ radon}$ (mSv/year)	0.43	0.63	2.13	4.27

Table IIa. Indicative dose (ID) from exposure to radon in indoor air by inhalation.

Exposure to radon in indoor air	Radon in indoor air (Bq/m^3l)			
	148 US Action Level	200 UK Action Level	400	1000
$ID_{indoor\ radon}$ (mSv/year)	3.73	5.04	10.08	20.16

Appendix 3. Radon concentrations in tap-water in selected areas in Scotland.

Area	Type of sample	Radon (Bq/l) (min - max)	Study
Private gw supplies in Highlands within high-risk area	boreholes	<10 - 218	Present study
	springs	<10 – 190	
	wells	15	
Private gw supplies in Aberdeenshire within high-risk area	boreholes	<10 - 106	
	springs	<10 - 494	
	wells	<10 - 95	
Private gw supplies in Perth and Kinross within high-risk area	boreholes	<10 - 65	
	springs	<10 - 41	
	wells	23 - 75	
Private gw supplies outwith the high-risk area	boreholes	<10 - 75	
	springs	<10 - 42	
	wells	<10 - 50	
Public gw supplies within high-risk area	Treatment plant	<10 - 197	
Public gw supplies outwith the high-risk area		<10 - 123	
Dumfries and Galloway	Tap-water	0.7 – 71.1	[12]
Grampian	Tap-water	0.6 – 62.2	
Highland	Tap-water	0.7 – 1.6	
Orkney	Tap-water	0.7	
Aberdeen (igneous rock)	Tap-water	40 – 76	[13]
Aberdeen (meta-sedimentary rock)	Tap-water	3 – 35	

References

[1] Council Directive2013/51/EURATOM of 22 October 2013 laying down requirements for the protection of the health of the general public with regard to radioactive substances in water intended for human consumption (OJ L 296/12, 7.11.2013, p.10)

[2] NRC (1998). Assessment of radon in drinking water, committee on the assessment of exposures to radon in drinking water, board on radiation effects research, Commission on Life Sciences, National Academy Press, NRC, Washington, D.C.

[3] Akerblom, G., & Lindgren, J. (1997). Mapping of groundwater radon potential. Uranium Exploration Data and Techniques Applied to the Preparation of Radioelement Maps, IAEA-TECDOC-980, IAEA, Vienna, 237-255.

[4] Deetjen P, editor. Scientific principles of the health treatments in Bad Gastein and Bad Hofgastein. Austria: Research Institute Gastein-Tauernregion; 1997. Available at http://www.zoologie.sbg.ac.at/gastein_report_e.htm.

[5] Song, G., Zhang, B., Wang, X., Gong, J., Chan, D., Bernett, J., & Lee, S. C. (2005). Indoor radon levels in selected hot spring hotels in Guangdong, China. *Science of the total environment* , 339(1), 63-70.

[6] Smith, B. M., Grune, W. N., Higgins, F. B., & Terril, J. G. (1961). Natural radioactivity in ground water supplies in Maine and New Hampshire*. Journal (American Water Works Association)* , 75-88

[7] Clark, D.W. and Briar D.W. (1993). Radon in ground water of western Montana. Water Fact sheet. U.S. Geological survey, U.S. Department of the Interior, Open-File Report 93-64.

[8] Salonen, L. (1994). 238U series radionuclides as a source of increased radioactivity in groundwater originating from Finnish bedrock. *IAHS Publications-Series of Proceedings and Reports-Intern Assoc. Hydrological Sciences*, 222, 71-84.

[9] Henshaw DL, Perryman J, Keitch PA et al., (1993). Radon in domestic water supplies in the UK. *Radiat Prot Dosim* 46 (4), 285-9.

[10] Smith, DM, WellhamD, and Gow C (1990) Radiological assessment or private water supplies in Cornawall. London, Department of the Environment, DoE Report No DOE/RW/90.083.

[11] UNSCEAR (1993). Sources and effects of ionizing radiation. United Nations Scientific Committee on the Effects of Atomic Radiation, Report to the General Assembly, with Scientific AnnexesUnited Nations, New York (1993).

[12] Allen, J. E., Camplin, G. C., Henshaw, D. L., Keitch, P. A., & Perryman, J. (1993). A UK national survey of radon in domestic water supplies. Physics Education, 28, 173-177.

[13] Al-Doorie, F. N., Heaton, B., & Martin, C. J. (1993). A study of ^{222}Rn in well water supplies in the area of Aberdeen, Scotland. *Journal of environmental radioactivity*, 18(2), 163-173.

CREW Facilitation Team
James Hutton Institute
Craigiebuckler
Aberdeen AB15 8QH
Scotland UK
Tel: +44 (0) 844 928 5428
Email: enquiries@crew.ac.uk
www.crew.ac.uk