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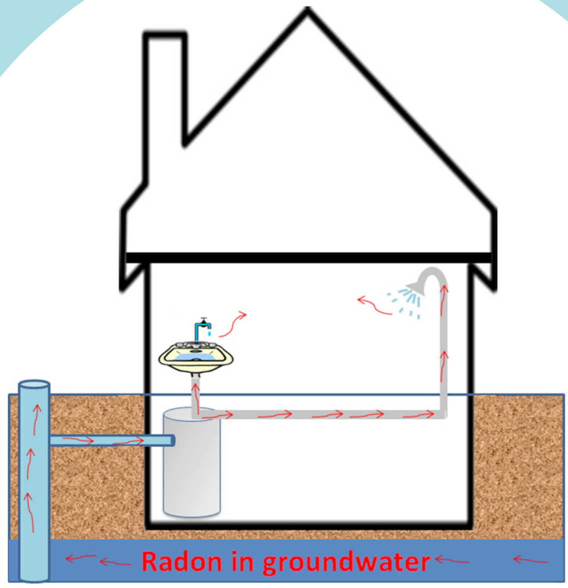
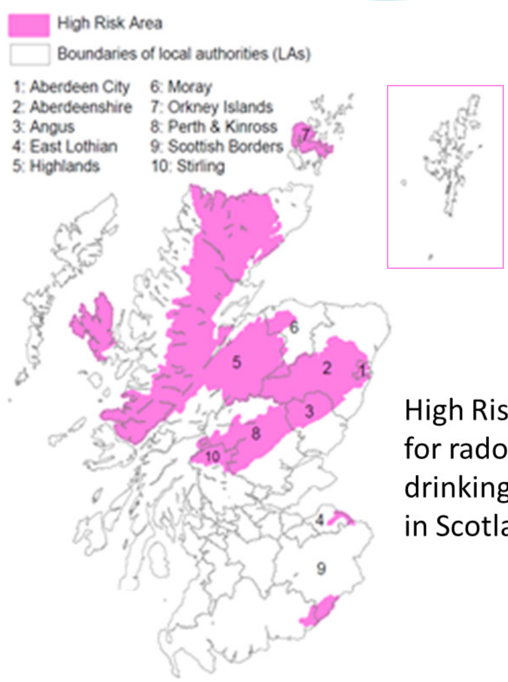
Radon in groundwater drinking water supplies in Scotland





High Risk Areas for radon in drinking water in Scotland

Scotland's centre of expertise for waters

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Abbreviations

α-radiation	alpha radiation
β-radiation	beta radiation
γ-radiation	gamma radiation
BGS	British Geological Survey (UK)
DWQR	Drinking Water Quality Regulator
HPA	Health Protection Agency (UK)
ID	Indicative dose
LAs	Local authorities
ICPR	International Conference on Pattern Recognition
NRC	National Research Council (USA)
PWS	Private Water Supplies
SEPA	Scottish Environment Protection Agency
SW	Scottish Water
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
WHO	World Health Organisation

Elements

Bi	Bismuth
Pb	Lead
Po	Polonium
Ra	Radium
Rn	Radon
U	Uranium

Contents

Executive Summary

The Questions

Are radon concentrations in drinking water 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 (parametric value) and action level for remedial action be in drinking water to protect public health from exposure to radon?

Key Findings

- This report presents the most recent and comprehensive evidence on radon concentrations in public and private groundwater supplies in Scotland; this evidence is essential for specifying regulations for radon in drinking water in Scotland to protect public health against radon.

- Overall, radon concentrations in groundwater drinking water supplies are significantly higher within than outwith the high-risk area (see map).

- Radon concentrations in the surveyed supplies range
  - o Between below 10 Bq/L and 494 Bq/L within the high-risk area, with highest values in private water supplies (PWS).
  - o Between below 10 Bq/L and 123 Bq/L outwith the high-risk area, with highest values in public water supplies.

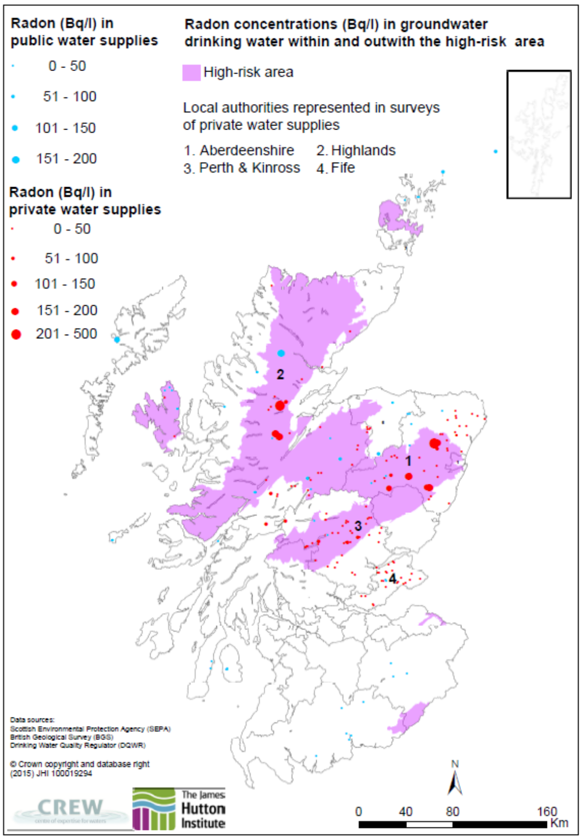
- Radon concentrations between 100 and 500 Bq/L are found in Aberdeenshire, in the wider area of the Highlands, and in the Outer Hebrides.

- Samples from type A-private water supplies (PWS) were collected at the source (points-of-entry); therefore radon in tap-water may be lower, or can be mitigated before reaching the tap.

- The radon values found in groundwater supplies within the high-risk area have the potential to:
  - o Increase the radon emanating from tap-water into indoor-air by 10-50 Bq/m^3.
  - o Result in an indicative dose of radiation by ingestion in the range of 0.18 - 0.9 mSv/yr; this is within the range of dose from exposure to radon in drinking water in the UK (0.01–1 mSv/yr).

- The highest radon concentration (i.e. 497 Bq/L) corresponds to an annual total indicative dose of radiation 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.

- The general population in Scotland is not chronically exposed to high radon in drinking water:
  - o Groundwater type A-private water supplies in the high-risk area found to have radon above 100 Bq/L are supplied as part of commercial or public activity (e.g. holiday lets and B&Bs); therefore exposure of the general public to radon in drinking water tends to be short-term.
  - o The range of radon concentrations in groundwater in the high-risk area from both public and type A-private water supplies are within the lower range of radon values in water in granite-rich and sandstone areas elsewhere in the world.



Radon concentrations in groundwater drinking water supplies.

Background

The European Commission has recently published a new Directive under the Euratom Treaty (Council Directive 2013/51/Euratom) laying down requirements for the concentrations of radioactive substances in water intended for human consumption. The Directive requires that Member States specify a parametric value for radon in drinking water (which should not be exceeded) between 100 and 1000 Bq/L and a radon action level at 1000 Bq/L, above which remedial action is required. Monitoring is required only where evidence from representative surveys shows that the specified parametric value for radon might be exceeded and at a monitoring frequency depending on volume of water consumed (i.e. one to two samples a year for type A private water supplies and depending on population size in a public water supply zone served by groundwater). An earlier CREW project (Akoumianaki et al. 2014) proposed that representative surveys for radon in drinking water should focus on the area, so-called high-risk area for radon in drinking water, 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.

Method

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 (point-of-entry) of 154 type A private groundwater supplies serving 1272 properties within and outwith the high-risk area were carried out to explore the effect of underlying geology on radon in groundwater. Radon was sampled and analysed by trained Scottish Water staff. Statistical tests (Mann-Whitney) were used for comparing radon concentrations from public and type A-private water supplies 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.

- All public groundwater supplies should be monitored to ensure compliance with the parametric value and action level. Mitigation and monitoring may target treatment works provided there is no adverse change in the concentration value between the sampling point and tap-water.

- Monitoring for radon to ensure compliance with the parametric value and action level in type A-private water supplies served by groundwater (wells, boreholes, and springs) should focus on the high-risk area.
  - o Monitoring should target tap-water but mitigation treatment should target points-of-entry.
  - o Awareness, mitigation advice, and monitoring should be planned by local authorities but mitigation treatment 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 groundwater type B-private water supplies within the high-risk area.

References

AKOUMIANAKI I, IBIYEMI, A & MACDONALD J 2014. Water Quality and Radon: Implications for Scotland of the Provisions and Scope of the Council Directive 2013/51/Euratom for radon in drinking water (CRW2013/17 – J203022). Available online at: crew.ac.uk/publications.

1.0 Introduction

1.1 Objectives

As part of an ongoing review of the implications of the Council Directive 2013/51/Euratom (1) on radon regulations in drinking water, a Scotland's Centre of Expertise for Waters (CREW) project recommended a map of areas of likely medium-, and high-risk of exposure to radon in drinking water (2). The map uses geological data from the British Geological Survey (BGS) and indoor-air data from the Health Protection Agency (HPA) to indicate 'what earth delivers' in terms of radon, and groundwater waterbody boundary data from Scottish Environment Protection Agency (SEPA) and BGS to identify groundwater public and private water supplies at risk of radon-contamination. 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 locations 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 HPA. 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.

The Directive requires that Member States specify a value for radon in drinking water between 100 and 1000 Bq/L, which should not be exceeded (i.e. parametric value) and a value at 1000 Bq/L, above which remedial action is required (i.e. action level). Monitoring is required only where evidence shows the specified parametric value might be exceeded.

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

- A radon target in drinking water (i.e. parametric value), an exceedance of which should trigger further investigation.
- 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 in drinking water.

1.2 Why and when is radon a public health 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 (3). 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.

Radon can present a health hazard by ingestion of freshly-drawn radon-contaminated groundwater before radon degasses to the indoor-air and by inhalation of radon emanating from tap-water (4). The National Research Council (NRC) in the USA has estimated that 11% of stomach cancers may result from drinking radon-contaminated water (4). However, breathing radon in the indoor-air is the primary public health risk from radon (3, 5, 6), with radon being the second leading cause of lung cancer in the general population in the UK and worldwide (3). The NRC has also estimated that approximately 89% of the fatal cancers caused by radon in drinking water are due to lung cancer from inhalation or radon released to indoor-air (4). It must be noted that only a small percentage of the total radon in indoor-air comes from tap-water, the greatest source being the ground beneath the home (3).

The earlier CREW report, which reviewed the evidence on the hydrogeological controls on radon concentrations in groundwater, showed that radon occurrence in drinking water is controlled by: underlying geology (i.e. bedrock type); hydrological processes influencing groundwater; and water supply type and management (2). Higher radon concentrations are expected in the groundwater than in surface waters and in areas underlain by uranium-bearing bedrock and associated soils (4, 5). Higher radon concentrations are also associated with groundwater bodies that are subject to frequent drilling (7-10) where radon degassing and radon-contaminated water transport or dilution with rainfall are restricted (11) and in karst formations during wet season (12). It must be noted that rainfall is well distributed throughout the year in most parts of Scotland (13) and karst is a very minor component of Scotland's geology, found mainly in remote upland areas (14). Therefore it is considered that any temporal, seasonal (meteorological) controls on radon in groundwater would be less important than spatial hydrogeological controls.

The major routes of exposure to radon in drinking water are by (3):

- Ingestion before radon degassing from tap-water to the indoor-air.
- Inhalation of the radon gas emanating from tap-water into the indoor-air. Inhalation of the solid particles of the radon progeny that may cling to indoor-air dust.

Waterborne radon can present a health hazard when water is freshly drawn from radon-contaminated groundwater supplies. 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 one Bq/L of radon in tap-water there is an increase by 0.1 Bq/m^3 of radon in indoor-air (3). There is higher risk of exposure to radon in drinking water from small public water networks or type A-private water supplies than from large public water supplies. Large public water supplies (generally serving more than 5000 people) come to households via large storage systems, often with long residence times. This allows for any radon originally present in drinking surface water or groundwater supplies to be released into the air or to decay to very low levels, varying between supplies, before reaching the consumer (3). In properties served by groundwater type A-private water supplies (PWS) and small public waterworks located in areas underlain by uranium-bearing bedrock, where higher radon concentrations are expected, the time between the pumping and consumption of tap-water may be well within radon's half-life (3, 4). In these cases, drinking water at point-of-use (tap) may be a health risk.

In response to the publication of the radon potential map (15), 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 (16). This policy includes all homes within the medium- and high-risk area for radon in groundwater proposed by CREW (2) for carrying out representative surveys to inform the decision the parametric value and action level for radon in drinking water in Scotland. However, the extent to which radon in drinking water poses a threat to the general public in Scotland is unknown.

2.0 Method

Representative surveys were carried out to explore the effect of underlying geology on radon concentrations in groundwater public water supplies and type A-PWS within and outwith the high-risk area and provide evidence for the range of radon concentrations in groundwater drinking water in Scotland.

In Scotland, 77 (i.e. 17%) public and 1497 (i.e. about 64%) type A-PWS take water from groundwater sources. Of these, only 24 public and 453 type A-PWS are located within the high-risk area. The surveys included all public groundwater supplies, and 154 randomly selected type A-PWS (53 boreholes, 88 springs, 13 wells) serving premises occupied most of the time in the Highlands, Aberdeenshire, Perth and Kinross, and Fife. Of the selected type A-PWS, 101 supplies 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 (points-of-entry) of type A-PWS. Annex I describes the sampling and statistical design and the methods of analyses of the 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 non-compliances.
- Mitigating radon concentrations found to exceed 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 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 make sure that the annual indicative dose of radiation 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 Annex II for these estimates).

According to the Directive's provisions, if radon concentrations are below 100 Bq/L, within and outwith the high-risk area, monitoring is not necessary. If, however, radon concentrations in groundwater are above 100 Bq/L, then more sampling is necessary to identify a fit-for-purpose parametric value and monitoring programme.

3.0 Results: radon concentrations within and outwith the high-risk area

Findings from the representative surveys in all public groundwater supplies and the selected type A-PWS served by wells, boreholes and springs show:

Overall

- 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 Directive's lower threshold for a parametric value, i.e. 100 Bq/L, in the high-risk area.
- Radon values in Scotland range from (Figure 1):
    - o Below 10 Bq/L up to 494 Bq/L within the high-risk area.
    - o Below 10 Bq/L up to 123 Bq/L outwith the high-risk area.
- Overall, radon concentrations exceeding 123 Bq/L are clearly found only in the high-risk area.
- The range of radon values in the surveyed groundwater public and type A-PWS in Aberdeenshire and the Highlands presented in this report are higher than the tap-water radon concentrations reported by (17) and (18) for wells in granite-rich and red sandstone areas in Scotland. i.e. Aberdeenshire, the Highlands, the Orkney Islands, and Dumfries and Galloway(radon concentrations per area are presented in Annex III). This may be because radon undergoes natural degassing and decay between abstraction points and points-of-entry, and tap-water.
- The range of radon concentrations within 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); see also the review of evidence on the hydrogeological controls on radon in drinking water by (2).

Public groundwater supplies

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

Groundwater type A-PWS

- Radon concentrations in groundwater type A-PWS range

  from (Figure 1):
  - o Below 10 Bq/L up to 494 Bq/L within the high-risk area
  - o Below 10 Bq/L up to 75 Bq/L outwith the high-risk area.

- In 13% of the surveyed type A-PWS, radon exceeds 100 Bq/L, with all exceedances found in springs and boreholes in Aberdeenshire and the Highlands.

- Only in 2% of the surveyed type A-PWS do radon values exceed 200 Bq/L.

- Differences in the radon concentrations between the high-risk area and the area outwith the high-risk area are not statistically significant at a local authority level.

- In about 50% of the surveyed type A-PWS, radon concentrations are below 10 Bq/L.

  - The groundwater type A-PWS in the high-risk area found to have radon above 100 B/l are supplied as part of commercial or public activity (e.g. holiday lets and B&Bs); therefore exposure of the general public to the health risks of radon above the minimum parametric value specified in the Directive in drinking water tends to be short-term.

- Monitoring 20 samples a week for radon in water in PWS-type A supplies within the high-risk area and analysis with liquid scintillation counting is feasible.

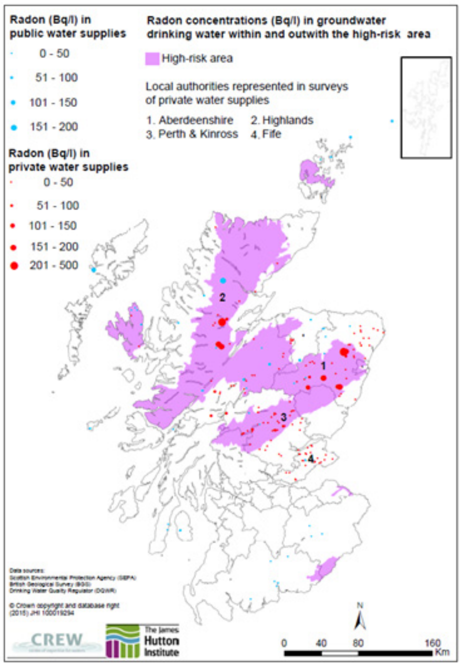


Figure 1. Radon concentrations (Bq/L) in public water supplies and type A-PWS served by groundwater sources within and outwith the high-risk

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

Underlying Geology	Radon in water (Bq/L)	References
Scotland (within high-risk area)	Type A-PWS (wells, boreholes, springs):<10 – 494 Public groundwater supplies: <10 - 197	Present Study
Scotland (outwith high-risk area)	Type A-PWS (wells, boreholes, springs):<10 – 123 Public groundwater supplies: <10 - 75	
Surface freshwater	<4	(19, 20)
Springs	50 – 740	(21, 22)
Wells dug in soil	Normal: 10-300	(19)
	Granite: 40-400	(23)
Wells in sedimentary rock	Normal: 10-50 (rarely 150)	(19)
	Metamorphic terrain: 37-370	(24)
Wells in crystalline rock	U-poor: 50-500	(25)
	U-rich granites: 300-4,000 (max=63,000)	(25, 26)
Wells in granite bedrock	10-42,000	(23, 27, 28)
Boreholes in granite bedrock	Max=80,000	(27, 29)
Public groundwater supplies in granite-rich areas	Max=1630	(27)

The implications of these findings in terms of exposure to ionising radiation can be summarised as follows:

- The higher radon concentrations in groundwater type A-PWS 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[1]. 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 (see Glossary) from ingestion of groundwater from the surveyed type A-PWS in the high-risk area can reach up to 0.18 - 0.9 mSv/yr (see Annex II for calculations). This range of indicative dose is within the range of annual dose from exposure to radon in drinking water in the UK, i.e. 0.01 – 1 mSv/yr (30, 31).

- The annual total indicative dose from both ingestion and inhalation of water containing 497 Bq/L (i.e. the highest concentration in the representative surveys) is approximately 2.14 mSv/yr (see Annex II for calculations). This dose is smaller than the total annual average radiation dose received by an individual in the UK, i.e. 2.5 mSv/yr, but higher than the annual average exposure due to radon from all sources in the UK, i.e. 1.3 mSv/yr (32).

4.0 Policy recommendations

The evidence from the representative surveys is essential for specifying regulations for radon in drinking water in Scotland. Given that radon concentrations at public water treatment plants and at point-of-entry of type A-PWS ranged between below 10Bq/L and 497 Bq/L, the parametric value should be between 100 and 500 Bq/L.

Identifying a parametric value for radon in drinking water should address the far greater risk from exposure to radon in the indoor-air. In this context, it is important to consider the cost of mitigating radon in water, including staff time and maintenance of mitigating devices, to achieve a low parametric value and justify this cost to the public on the basis of evidence. For example, 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 (4). 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 remedial action for protection from high exposure to radon.

Monitoring and mitigation of radon are generally different in public and private groundwater supplies. Monitoring at public water supplies is usually carried out before water enters the distribution network (i.e. at treatment plants) at the water supply zone scale. Groundwater in public water treatment plants may undergo a process, i.e. aeration, to ensure that radon is mitigated before it enters the distribution network (4, 6). This approach is suitable and feasible for the public groundwater supplies over Scotland.

Monitoring for radon in small supplies, community or individual wells, may be sampled before (i.e. at the points-of-entry) or at the tap (i.e. at the points-of-use). Radon mitigation in small 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, as in the USA (4). This approach is suitable for groundwater type A- and type B-PWS within the high-risk area in Scotland.

Specific recommendations and their rationale are presented below.

4.1 Monitoring

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

- For both public and private water supplies (see also section 1.2):
  - o Seasonal monitoring is not required to test compliance with the parametric value and the action level but year-to-year monitoring is necessary to test public supply zone or type A-PWS conditions. However, it would be useful to identify erodible rock formations within the high-risk area, and in consultation with BGS, carry out seasonal monitoring to test whether and how any temporal variations in meteorological variables (e.g. rainfall, snow, barometric pressure, and temperature) affect radon in groundwater drinking water supplies.
  - o Monitoring is not required in surface water supplies.

- For public water supplies:
  - o Monitoring in all public groundwater supplies is required when the residence time of water in treatment plants is expected to be 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.
  - o Given that the residence time of water in treatment plants may be unknown and that public groundwater supplies are generally small (i.e. serving fewer than 5000 people), all public groundwater supplies should be monitored for assessing compliance with the radon parametric value.

- For private water supplies:
  - o 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.
  - o Local authorities must plan for raising awareness and providing advice to both users and owners of these groundwater supplies to ensure mitigation of radon in water between source and tap.
  - o Monitoring of private groundwater supplies should target points of compliance, i.e. tap-water.
  - o Mitigation of radon in groundwater type A- and type B-PWS is the responsibility of users and owners. Specific recommendations on radon mitigation in PWS are outwith the scope of this report.
  - o Replicate tap-water samples should be collected from properties served by the same type-A PWS; recording the number of properties and type and source of a particular

[1] Radon transfer coefficient from water to air= 10^{-4} (See section 1.2).

supply will help to assess any causes of variation in radon levels between properties and from year-to-year, and inform mitigation practice before the water reaches the tap.

4.2 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 certain limitations for both the parametric value and action level for radon in water to be between 100 and 500 Bq/L.

The first limitation refers to costly and difficult implementation. Ensuring compliance with the regulations involves sampling representative of 'areas of likely exposure', laboratory analysis of samples within appropriate time from sampling, 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 radon awareness and mitigation advice in all type-A PWS within the high-risk area, but target monitoring and mitigation action, if required, only in the high-risk area of the Highlands and Aberdeenshire, where the representative surveys of this project demonstrated radon concentrations exceeding 100 Bq/L.

The second limitation refers to insufficient protection of the population from exposure to the hazards of ionising radiation. The Environment Protection Agency in the US (US EPA) 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 US EPA in developing national drinking water standards (33). In this regard, the parametric value should be below 148 Bq/L. However, the high-risk area in Scotland contains commercial and public premises; therefore the risks from chronic exposure to radon in water of type A-PWS at or above 148 Bq/L are negligible. On the other hand, it is not easy to infer risks from chronic exposure to radon for the users of groundwater type B-PWS in the high-risk area without representative surveys for type B supplies and without knowing the residence time of water in storage tanks 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, in a cost-effective manner, 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 (17, 19, 24, 25); such increases of radon in indoor-air correspond to a rise in lung cancer risk by 10 to 16% (34-37).

4.3 Mitigation in private water supplies

Radon can be removed from water either before reaching the tap or at the tap (4, 7, 38).

- 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.
    - 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 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 including bathroom.

5.0 Conclusion

Representative surveys provided the evidence needed to inform DWQR of the implications for Scotland of the provisional regulations of the Directive for radon in water. 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, were analysed in detail in an earlier CREW report (2). This CREW report presents radon concentrations in groundwater in drinking water in Scotland.

The key findings are:

- This report presents the most recent and comprehensive evidence on radon concentrations in public and private groundwater supplies in Scotland; this evidence is essential for specifying regulations for radon in drinking water in Scotland to protect public health against radon.

- Overall, radon concentrations in groundwater drinking water supplies are significantly higher within than outwith the high-risk area.

- Radon concentrations in the surveyed supplies range
    - Between below 10 Bq/L and 494 Bq/L within the high-risk area, with highest values in private water supplies (PWS).
    - Between below 10 Bq/L and 123 Bq/L outwith the high-risk area, with highest values in public water supplies.

- Radon concentrations between 100 and 500 Bq/L are found in Aberdeenshire, in the wider area of the Highlands, and in the Outer Hebrides.

- Samples from type A-private water supplies (PWS) were collected at the source (points-of entry); therefore radon in tap-water may be lower, or can be mitigated before reaching the tap.

- The radon values found in groundwater supplies within the high-risk area have the potential to:
  - o Increase the radon emanating from tap-water into indoor-air by 10-50 Bq/m^3.
  - o Result in an indicative dose of radiation by ingestion in the range of 0.18 - 0.9 mSv/yr; this is within the range of dose from exposure to radon in drinking water in the UK (0.01–1 mSv/yr).

- The highest radon concentration (i.e. 497 Bq/L) corresponds to an annual total indicative dose of radiation 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.

- The general population in Scotland is not chronically exposed to high radon in drinking water:
  - o Groundwater type A-private water supplies in the high-risk area found to have radon above 100 Bq/L are supplied as part of commercial or public activity (e.g. holiday lets and B&Bs); therefore exposure of the general public to radon in drinking water tends to be short-term.
  - o The range of radon concentrations in groundwater in the high-risk area from both public and type A-private water supplies are within the lower range of radon values in water in granite-rich and sandstone areas elsewhere in the world.

This CREW report also provides recommendations for the monitoring and mitigation of radon in all groundwater public water supplies at the treatment plants and for private water supplies in the high-risk area.

The recommendations developed in this report are:

- 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.

- All public groundwater supplies should be monitored to ensure compliance with the parametric value and action level. Mitigation and monitoring may target treatment works provided there is no adverse change in the concentration value between the sampling point and tap-water.

- Monitoring for radon to ensure compliance with the parametric value and action level in type A-private water supplies served by groundwater (wells, boreholes, and springs) should focus on the high-risk area.
  - o Monitoring should target tap-water but mitigation treatment should target points-of-entry.
  - o Awareness, mitigation advice, and monitoring should be planned by local authorities but mitigation treatment 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 groundwater type B-private water supplies within the high-risk area.

The findings and recommendations of this report will support the transposition of the Council Directive 2013/51/Euratom into Scots law by November 2015.

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Glossary

(Based on references: 1, 3, 4, 32, 33).

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 radioctivity and is equivalent to one disintegration per second (dps).

Detriment is a term used to describe the 'total harm' experienced by exposing a population (and their descendants) to internal radiation. ICRP uses detriment to effectively sum all the Risks (probabilities) that exposure to ionising radiations might produce. For example it will include probability of fatal cancer induction, non-fatal cancer induction (and therefore years of life lost).
It therefore as the dimensions of probability and thus can be expressed as a risk. Radiation detriment is developed and used for deriving dose limits.

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' in the Directive 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.

Ionising radiation: According to the Ionising Radiations Regulations 1999, UK 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 X 1015 Hertz or more capable of producing ions directly or indirectly'.

Parametric value in the Directive means the value of radioactive substances in water intended for human consumption above which Member States shall assess whether the presence of radioactive 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.

Radioactive decay describes the process whereby 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 1 Sv = 100 Rem.

Annex I: Design of baseline representative sampling and sample analyses

Representative surveys were designed to ensure that the range of radon concentrations in groundwater public and type A-PWS within and outwith the high-risk area is captured to inform decision on parametric value and action level for radon in drinking water in Scotland. No surveys were carried out in groundwater type B- PWS.

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. The selected PWS-type A serve 1272 properties in the following local authorities: Aberdeenshire, Highlands, Perth and Kinross, and Fife.

The PWS for representative surveys were randomly selected from a list of all PWS serving premises occupied most of the time in the Highlands, Aberdeenshire, Perth and Kinross, and Fife. All of the surveyed PWS served one or a combination of types of commercial activity, i.e. holiday let, caravan parks, visitor/activity centre, deer larder, workplace, food preparation facility, hotel. Very few supplies, in addition to serving a commercial activity, served a school, care home or households.

Water samples for radon were collected and processed by trained Scottish Water staff. Laboratory analyses were carried out using liquid scintillation counting with a capacity to analyse 20 samples a week.

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.

Annex II. Summary of annual indicative dose (ID) values from 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 (UNSCEAR 1993: Annex B):

$ID_{ingestion} = Conversion_{ingestion} \times Consumption_{tap\text{-}water} \times Radon_{tap\text{-}water}$ (Equation 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 (UNSCEAR 1993; NRC 1999) or 1.0 X 10^{-8} Sv/Bq (UNSCEAR 1993);

$Consumption_{tap\text{-}water}$: average annual consumption of water;

$Radon_{tap\text{-}water}$: average radon concentration in drinking water.

UNSCEAR (1993: Annex B) 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:

$ID_{inhalation} = Conversion_{inhalation} \times Radon_{tap\text{-}water} \times Transferwater\ to\ air \times F_{radon\ to\ progeny} \times T_{indoors}$ (Equation 2)

where,

$Conversion_{inhalation}$: conversion factor of committed effective dose from inhalation of waterborne radon equal to 9 X 10^{-9} Sv/Bq (UNSCEAR 1993: Annex B);

$Radon_{tap\text{-}water}$: annual average radon concentration in drinking water;
$Transfer_{water\ to\ air}$: Radon transfer coefficient from tap-water to air, equal to 0.1 Bq/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.

The ID from inhalation of indoor radon from both ground and waterborne sources (IDindoor radon), can be calculated using the following equation (UNSCEAR 1993: Annex B):

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

where,

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

Using Equations 1, 2 and 3 for a range of $Radon_{tap\text{-}water}$ and $Radon_{indoor\text{-}air}$ 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_Annex II). Annual drinking water intake has been estimated for reference individuals.

The estimates are 500 L/yr for adults, 350 L/yr for children and 150 L/yr for infants (ICRP 1975). However, WHO recommends an average daily intake equal to 2 L per day (WHO 1994).

Table 4. Summary of ID values from exposure to waterborne radon by ingestion and inhalation and to indoor-air radon by inhalation corresponding to a range of radon concentrations in drinking water and indoor-air, respectively.

Exposure to radon in drinking water	Radon in drinking water (Bq/L)						
	11 *	100 **	148 ***	200	400	800	1000 #
IDingestion (mSv/yr)	0.02	0.18	0.3	0.4	0.7	1.4	1.8
IDinhalation (mSv/yr)	0.03	0.25	0.4	0.5	1.0	2.0	2.5
Total ID from waterborne radon (mSv/yr)	0.05	0.43	0.7	0.9	1.7	3.4	4.3

*US EPA parametric value for radon in drinking water
**EU Minimum parametric value for radon in drinking water
***US EPA action level for radon in drinking water
#EU Maximum parametric value/ action level for radon in drinking water

Exposure to radon in indoor-air	Radon in indoor-air (Bq/m^3)						
	100^	148^^	200 ^^^	400	600	800	1000
IDindoor radon (mSv/yr)	2.52	3.73	5.04	10.08	15.12	17.64	20.16

^ UK Target Level ^^ US action level ^^^ UK action level

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Annex III. Radon concentrations in tap-water in selected areas in Scotland.

Area	Type of supply	Radon (Bq/L) (min - max)	References
Private groundwater supplies in Highlands within high-risk area	Boreholes	<10 - 218	Present study
	Springs	<10 – 190	
	Wells	15	
Private groundwater supplies in Aberdeenshire within high-risk area	Boreholes	<10 - 106	
	Springs	<10 - 494	
	Wells	<10 - 95	
Private groundwater supplies in Perth and Kinross within high-risk area	Boreholes	<10 - 65	
	Springs	<10 - 41	
	Wells	23 - 75	
Private groundwater supplies outwith the high-risk area	Boreholes	<10 - 75	
	Springs	<10 - 42	
	Wells	<10 - 50	
Public groundwater supplies within high-risk area	Treatment plant	<10 - 197	
Public groundwater supplies outwith the high-risk area		<10 - 123	
Dumfries and Galloway	Tap-water	0.7 – 71.1	Allen et al. 1993
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	Al-Doorie et al. 1993
Aberdeen (meta-sedimentary rock)	Tap-water	3 – 35	

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