

Water Quality and Radon: Implications for Scotland of the Provisions and Scope of the Council Directive 2013/51/Euratom



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Abbreviations

AGIR	Advisory Group on Ionising Radiation (UK)
BGS	British Geological Survey (UK)
DWQR	Drinking Water Quality Regulator
HPA	Health Protection Agency (UK)
ICPR	International Conference on Pattern Recognition
LAs	Local Authorities
NRC	National Research Council (USA)
PWS Regulations	Private Water Supplies 2006 (Scotland) Regulations
SW	Scottish Water
SEPA	Scottish Environment Protection Agency
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
WHO	World Health Organisation
α	alpha radiation
β	beta radiation
γ	gamma radiation

Elements

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

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Executive Summary

Objective

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. As part of an on-going review of the implications of the Directive for Scotland, the Drinking Water Quality Regulator (DWQR) commissioned the Centre of Expertise for Waters (CREW) to collate evidence on the presence of radon in drinking water and create a map of risk areas of potential exposure to radon in drinking water from public and private water supplies. The evidence review and risk map will inform where any surveys are required to help assess whether the presence of radon in drinking water poses a risk to human health and whether remedial action is required to comply with the requirements for the protection of human health from radioactivity.

Background

Radon (radon-222) is a naturally occurring, water-soluble, geogenic gas produced by the radioactive decay of uranium-bearing rock formations. It emits alpha radiation and has a half-life of 3.8 days. The radioactive products of its decay chain (radon progeny) are all solid and give off either alpha (e.g. polonium) or beta (lead and bismuth) radiation.

The Directive requires Member States to specify a value for radon between 100 and 1000 Bq/l, which should not be exceeded (parametric value), and a radon Action Level at 1000 Bq/l, above which remedial action is required. Monitoring is required only where representative surveys, or other reliable information, indicate that the parametric value laid down is exceeded. For radon, surveys and historical data should identify how the underlying geology and hydrology, radioactivity of rock or soil, and well type affect concentrations of radon and radon radioactive decay products in drinking water. The Directive's provisions for radon must be transposed to national legislation by November 2015.

Radon in drinking water can present a potential health hazard in three ways:

- i. By ingestion of radon-contaminated groundwater before radon degassing to indoor air.
- ii. By inhalation of the radon gas that escapes tap water; only a small percentage of the total radon in indoor air comes from tap water, the greatest source being the ground beneath the home.
- iii. By inhalation of the radon progeny that may cling on dust particles found in the indoor air.

The risk due to inhalation of radon emanating from tap water is almost twice as high as the risk due to ingestion of radon contaminated water. It is known that in certain areas, such as Aberdeenshire, Helmsdale, and the Orkney Islands areas, more than 10% of homes have high radon gas in indoor air.

Public water supplies come to households via large storage systems with long residence times that allow radon to escape into air or decay to very low levels before leaving the treatment plant. The time between pumping and consumption of water from small private water supplies or small public networks, however, is well within radon's half-time (i.e. 4 days), which is the time required for one half of a given concentration of radon to decay. In Scotland, the radon content of these supplies is not known but therefore this project aims to inform the DWQR on risk areas of potential exposure to radon in drinking water supplies.

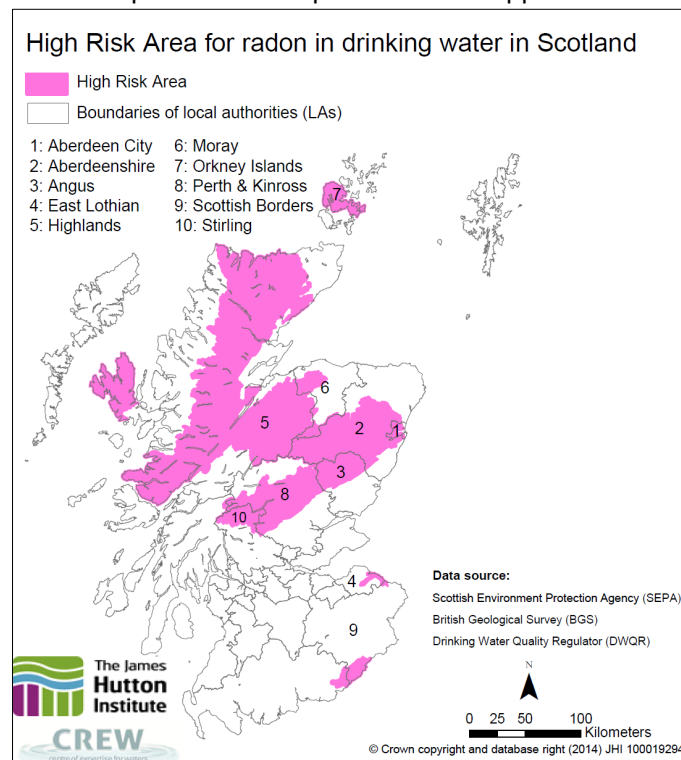
Approach to help assess the implications of the Directive's (2013/51/Euratom) provisions for radon

Our approach involves three steps. Firstly, we review the evidence (from regulatory and other agencies and from the scientific literature) on radon occurrence in drinking water supplies and radon effects on human health. Secondly, we develop a method to identify 'areas of likely high exposure',

to radon in drinking water due to underlying geology, as required in the Directive. The method builds on the radon potential map for Scotland, which is a 5-km grid of the percentage of homes having radon gas concentrations in indoor air at or above the level for remedial action specified by the Health Protection Agency (HPA). Radon potential is mapped in relation to the geological background using data from the British Geological Survey (BGS), so it indicates ‘what earth delivers’ in terms of radon. A radon potential above 10% refers to high risk; a radon potential between 5% and 10% refers to medium risk. By joining groundwater bodies with the radon potential map it is possible to identify which groundwater supplies may have high radon content and explore Risk Area scenarios for further policy action. Thirdly, we discuss the implications of the key findings in the context of the Directive’s provisions for a parametric value, Action Level and monitoring for radon in Scotland.

Key findings

1. There is limited evidence on radon levels in private water supplies in Scotland. However, the data that do exist are reliable and suggest radon levels are below the minimum parametric value specified in the Directive.
2. Radon occurrence in water is controlled by underlying geology. Radon is higher in:
 - Areas with uranium-bearing bedrock and associated soils. In Scotland, such areas are found mainly in Aberdeenshire, Helmsdale and the Orkney Islands but also in the Southern Uplands, the Argyll area and in limestone throughout Scotland.
 - Groundwater bodies where contact with the minerals of the uranium-rich source material is enhanced (e.g. through frequent drilling) and emanation, transport, or dilution is restricted;
 - Groundwater than in surface water supplies;
 - Cold water because radon solubility decreases rapidly with increased temperature.
 - Areas with a high percentage probability of homes having radon at or above the Action Level for indoor air due to the underlying geology. Indoor air is used as a proxy of radon in soil.
 - Four Risk Area scenarios can be identified. Our assessment shows that the High Risk Area scenario for radon in groundwater includes 24 public and 453 private water supplies spread in ten local authorities shown in the map below. If the High Risk Area is expanded to include groundwater bodies linked with areas of medium radon potential, the Medium plus High Risk Area scenario includes 40 public and 739 private water supplies in 20 local authorities.



Policy Recommendations

The Directive requires Member States to 'direct action in areas of likely high exposure' to radon in drinking water and to ensure that failure to comply with the parametric value laid down is immediately investigated in order to identify whether it poses a risk to human health which requires action. Based on the results of this work, we recommend:

1. **Target monitoring in 'areas of likely high exposure' to radon in drinking water.** Monitoring in the High Risk Area scenario to assess and validate the risk mapping is the best option. It provides organisational advantages, such as the feasibility of a monitoring program and representativeness of 'areas of likely high exposure'. The Medium plus High Risk scenario provides the potential to develop synergies with the already existing indoor air radon policy of the Scottish Government, which is targeted at areas where more than 5% of homes have radon in indoor air at or above Action Level.
2. **Lay down achievable Action Level and parametric value for radon**
 - Focusing on protection from exposure by inhalation, which is the greatest hazard from exposure to radon in water; this favours a parametric value at the upper end of the range in the Directive's recommendations.
 - Adopting a single value for Action Level and parametric value to allow for effectively communicating and implementing mitigation measures to protect the general public.
 - Conducting baseline surveys to inform on what radon concentration is achievable depending on the range of values in tap water and type of water supplies needing mitigation.
 - Developing a holistic approach to mitigate and protect the population from exposure to radon from all sources e.g. water containing 1000 Bq/l of radon and a home with indoor air radon at 200 Bq/m³ result in similar levels of exposure to radon. Combined mitigation measures will reduce exposure, ensure cost-effectiveness, and send a clear message to the public.
 - Reflecting on lessons learned from international examples of policy for radon in water.
3. **Action for Scottish Water**
 - Monitoring of surface water supplies is not required.
 - Sampling and mitigation are necessary only in groundwater supplies with short residence time in treatment plants; sampling and mitigation before water enters the distribution network is recommended.
4. **Action for Local Authorities**
 - Monitoring of surface water supplies is not required.
 - Baseline surveys in the tap water from groundwater supplies within the selected Risk Area scenario are necessary.
 - Mitigation should take place at point of entry to ensure effectiveness of measures.

1. Introduction

The European Commission published a new Directive under the Euratom Treaty (Council Directive 2013/51/Euratom, hereafter reported as the Directive) laying down requirements for the concentrations of radioactive substances in water intended for human consumption. As part of an on-going review of the implications of the Directive for Scotland, the Drinking Water Quality Regulator (DWQR) commissioned the Centre of Expertise for Waters (CREW) to collate evidence on the presence of radon in drinking water and, create a map of 'areas of likely high exposure'. The evidence review and risk map will inform whether and where any surveys are required in public and private water supplies to help identify a parametric value and monitoring frequencies for radon in Scotland. The CREW output is aligned with the results of parallel surveys by the Drinking Water Inspectorate (DWI) in England and Wales before transposing the new Directive to national legislation in Scotland.

2. Directive 2013/51/Euratom

Council Directive 2013/51/Euratom [1] requirements for tritium and total indicative dose (ID) are consistent with the provisions and scope of the Drinking Water Directive (DWD) (Table 1). In addition to the DWD requirements, Member states must specify a value for radon between 100 and 1000 Bq/l, which should not be exceeded (parametric value), and a radon Action Level at 1000 Bq/l, above which remedial action is required (Table 1). Monitoring is required only where representative surveys, or other reliable information, indicate that the parametric values laid down are exceeded; for radon, surveys and historical data should identify how the underlying geology and hydrology, radioactivity of rock or soil, and well type affect concentrations of radon and radon progeny in drinking water. The new Directive, and especially its novel provisions for radon and the activities of its short-lived decay products (radon progeny), must be transposed to national legislation by November 2015.

Table 1. Recommendations of the new Directive for tritium, total indicative dose (ID), and radon¹.

Provisions and scope	Directive's recommendations [1]	Drinking Water Directive [2]	
		'Regulations'	'PWS Regulations'
Radon parametric value (Bq/l)	100 - 1000	-	-
Radon Action Level (Bq/l)	1000	-	-
Tritium parametric value (Bq/l)	≤ 100	≤ 100	≤ 100
Gross alpha screening level (Bq/l)*	≤ 0.1	≤ 0.1	≤ 0.1
Gross Beta screening level (Bq/l)*	≤ 1	≤ 1	≤ 1
Total indicative dose (ID) from annual ingestion of water (mSv)**	≤ 0.1,	≤ 0.1	≤ 0.1
Exempt from monitoring	<ul style="list-style-type: none"> • Supplies where parametric values are not exceeded • Domestic supplies serving <50 persons 		

*required for the calculation of ID; if gross alpha or beta activity exceed screening levels analysis for specific radionuclides shall be required.

**excluding tritium, potassium-40, radon and short-lived radon decay products, i.e. polonium-210 and lead-210.

¹ Requirements for tritium and ID have already been transposed as the Water Supply (Water Quality) (Scotland) Regulations 2001 ('Regulations') for public water supplies and the Private Water Supplies (Scotland) Regulations 2006 ('PWS Regulations') in line with the provisions of the DWD.

3. Why is radon in drinking water a health problem?

Radon (radon-222) is a naturally occurring, water-soluble, geogenic gas produced by the radioactive decay of uranium-bearing rock formations (Figure 1). Radon emits alpha and gamma radiation and has a half-life of 3.8 days; the radioactive products of the radon decay chain (radon progeny) are solid and give off either alpha and gamma radiation (e.g. polonium) or beta and gamma radiation (lead and bismuth). Radon is the second leading cause of lung cancer in the general population in many countries, including the UK [3, 4 5]. Other health effects of radon have not consistently been demonstrated but, very high radiation doses to infants and young children due to consumption of water containing radon have been shown [6, 7, 8, 9].

Radon characteristics	Radon occurrence	Radon health effects
<ul style="list-style-type: none"> • Gas • Water soluble • Inert gas • Odourless • Tasteless • Naturally occurring • Product of uranium-238 decay Half-life: 3.86 days • Radon decay chain (progeny) <ul style="list-style-type: none"> • Solid alpha and beta particles (e.g. polonium, lead) 	<ul style="list-style-type: none"> • Ubiquitous • Bedrock rich in uranium-238 • Groundwater • Soils • Outdoor air • Drinking water supplies, especially groundwater • Indoor air via emanation from ground beneath home and degassing from tap water 	<ul style="list-style-type: none"> • Ingestion (radon gas) <ul style="list-style-type: none"> • Stomach cancer • Inhalation (radon solid progeny) <ul style="list-style-type: none"> • Lung cancer

Figure 1. Radon: characteristics, occurrence, and health effects to the general public (WHO, 2009).

Radon in drinking water can present a health hazard in three ways:

- By ingestion of freshly drawn radon-contaminated groundwater before radon degasses to the indoor air. More than 90% of radiation is received by the stomach [10, 11, 12] and is primarily due to radon gas itself [10].
- By inhalation of the radon gas that escapes tap water from freshly drawn radon-contaminated public or private groundwater supplies. Only a small percentage of the total radon in indoor air comes from tap water, however, the greatest source is the ground beneath the home [3].
- By inhalation of the solid particles of the radon decay-series (radon progeny) that may cling to dust particles found in the indoor air [13, 14].

Public water supplies come to households via large storage systems 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 before leaving the treatment plant [15, 3]. In homes served by private domestic supplies, however, and small public waterworks, especially those using freshly drawn groundwater in areas with uranium-bearing bedrock, the time between pumping and consumption of tap water is well within radon's half-life [15].

In Scotland 17 % of public water and more than 64% of type A private water supplies take water from groundwater sources. Although the Scottish Government recently published a map of radon affected areas, relating underlying geology with indoor air radon levels², it is not known whether or how many groundwater supplies are within these areas. In addition, until the publication of the new Directive,

²<http://www.scotland.gov.uk/news/releases/2009/04/23101833>.

there was no statutory requirement to monitor radon in these supplies. The extent to which radon in drinking water poses a threat to the general public in Scotland is therefore not known.

4. How can implications of the Directive's provisions for radon be assessed?

This report reviews regulatory datasets and evidence on the hydrogeological controls on radon occurrence in drinking water. This will help predict 'areas of likely high exposure' to radon in drinking water. It will also help assess the implications for Scotland of the provisions of the Directive in terms of likely exceedances of the specified radon minimum parametric value and Action Level. Our approach involves three steps (Table 2):

- Firstly, we review regulatory and research evidence for indications of radon occurrence (e.g. elevated values of ID and gross alpha and beta activities in the water environment) and their effects on the health of the general public³.
- Secondly, we develop recommendations for 'areas of likely high exposure' to radon in drinking water and, accordingly, create a risk map for water supplies in Scotland (Section 4). The steps followed to create the risk map using ArcGIS software are presented in Appendix I.
- Thirdly, we discuss the implications of the key findings in the context of the Directive's provisions for a parametric value, Action Level and monitoring for radon in Scotland.

³ Data from water treatment plants, involving operations that may cause a significant increase in the exposure of workers to naturally occurring radon and radon daughter elements, collected under the provisions and scope of Council Directive 96/29/Euratom, are not examined.

Table 2. Outline of the approach and data analysed to help assess the implications for Scotland of the Directive's provisions for radon.

Step	Source of data	Data description	Policy driver for collection of data
Step 1: Review	SEPA	Data from monitoring public water supplies representative of sources (rivers, reservoirs, boreholes) and near radioactive waste discharge points ⁴ .	Article 35 of the Euratom Treaty for the monitoring of the level of radioactivity in the air, water and soil ⁵
	Scottish Water (SW)-DWQR	Data from monitoring public water / private drinking water supplies (PWS) / consultation with SW and DWQR.	Drinking Water Directive [2]
	Local Authorities – DWQR:	Data from monitoring PWS	Drinking Water Directive [2]
	Policy – Health guidelines	<ul style="list-style-type: none"> • Health effects of radon in drinking water • Effective dose from radon in drinking water • Parametric values and action level in EU, UK, US 	<ul style="list-style-type: none"> • WHO guidelines on exposure to radon [3, 14] • Commission's Recommendation 2001/928/Euratom (radon in water) [16] • Council Directive 96/29/Euratom (basic safety standards) [17] • National legislation from a variety of countries
	Peer reviewed literature	<ul style="list-style-type: none"> • Radon concentrations in drinking water in Scotland • Underlying geology and hydrology 	<ul style="list-style-type: none"> • National legislation from a variety of countries • WHO guidelines on exposure to radon [3, 14]
Step 2: Risk map	BGS-HPA	Radon potential map for indoor air	<ul style="list-style-type: none"> • Recommendations of the independent Advisory Group on Ionising Radiation-HPA [5]
	SEPA-BGS	Groundwater waterbody boundaries	Water Framework Directive [18]
	DWQR	Locations of public and private water supplies (type / source)	Drinking Water Directive [2]
Step 3: Implications	Current report	<ul style="list-style-type: none"> • Radon Risk Area for drinking Water • Effective dose from waterborne radon • Number and type of public and type A PWS within Risk Area 	Council Directive 2013/51/Euratom (Directive) [1]

⁴ Published annually in the Radioactivity in Food and the Environment (RIFE) report series since 1995 (http://www.sepa.org.uk/radioactive_substances/publications/rife_reports.aspx).

⁵ ec.europa.eu/energy/nuclear/radiation.../main_findings_spanish_en.pdf.

5. What do we know about levels and controls of exposure to radon in drinking water?

5.1 What does regulatory evidence tell us about radon in drinking water in Scotland?

Gross alpha and gross beta levels in representative public drinking water sources published in the RIFE reports since 1995 are well below the screening levels recommended by WHO (i.e. 0.5 and 1 Bq/l, respectively) and laid down by the DWD (i.e. 0.1 and 1 Bq/l, respectively). In 2012, the mean annual dose from consuming drinking water in the UK is mainly due to exposure to natural radionuclides and assessed as 0.027 mSv⁶. In addition, there is no evidence for contamination of public water supplies with radioactive waste or exposure to radon in drinking water in Scotland.

Scottish Water (SW) calculates ID in public water supplies only if the screening values for gross alpha, gross beta or tritium activities specified in the Regulations are exceeded. In the case of exceedance, SW resamples weekly the supply zone for five weeks to determine concentrations of individual radionuclides on the basis of available information on the likely source of contamination, and compares their levels with the guidance levels for ID. The outcome of this further evaluation may indicate that no action is required or that further evaluation (i.e. weekly sampling) is necessary before a decision can be made on what remedial action applies to the case. Interviewing SW for the outcome of these audits and crosschecking with published monitoring data and regulatory correspondence (i.e. letters from SW to DWQR) shows compliance with specified screening levels in all but two cases. There is no evidence, however, that the small deviations from specified screening levels in these two cases could be related to radon contamination.

Radon and radon progeny are not significant for any surface PWS in the UK⁷. In addition, routine monitoring of ID and gross alpha and beta activities is not taking place. A Food Standards Agency (FSA) publication in 2004⁸ reports that, based on evidence, there is no need to require local authorities to monitor type A PWS in Scotland for ID. This is because 'if a monitoring local authority is satisfied that on the basis of other monitoring carried out the Total Indicative Dose in a supply is well below the prescribed value, the authority may seek a regulation 24 notice from the Scottish Ministers confirming that the supply need not be monitored in respect of Total Indicative Dose'⁹.

Overall, this evidence does not reveal high exposure to radionuclides in surface or groundwater drinking water supplies in Scotland from geogenic or any artificial sources of radon. In the case of geogenic radon, this conclusion is based on the assumption that likely high radon concentrations in drinking water would have been captured in the monitoring of gross alpha or beta activities. It is uncertain, however, whether the regulatory evidence indicates low concentrations of radon and radon progeny in drinking water, or, especially in the case of PWS, lack of knowledge due to lack of measurements of radon, or gross alpha and beta activities.

5.2 What is the expected radiation dose from exposure to waterborne radon?

Radon contributes by about 1.3 mSv to the total annual average radiation dose received by an individual in the UK, i.e. 2.5 mSv¹⁰ [19; 4]. This dose is very small compared with the dose limit to occupational exposure, i.e. 20 mSv, but it is higher than the UK average ID from drinking 1l of tap water per day, i.e. 0.01 mSv (Table 3). However, ID may be in the order of 1 mSv from private water supplies in the UK, assuming that all radon is retained within the water [21] (Table 3). In this context, ID from radon-contaminated drinking water may significantly contribute to total radiation dose and must thus be calculated.

⁶ http://www.sepa.org.uk/radioactive_substances/publications/rife_reports.aspx

⁷ www.scotland.gov.uk/Resource/Doc/155498/0041750.pdf

⁸ <http://www.food.gov.uk/science/surveillance/fsis2004branch/fsis6704>

⁹ www.opsi.gov.uk/legislation/scotland/ssi2006/20060209.htm

¹⁰ <https://www.gov.uk/government/publications/ionising-radiation-dose-comparisons/ionising-radiation-dose-comparisons>

Table 3. Radiation dose from a variety of exposures in comparison with ID from radon in water.

Type of exposure to ionising radiation	Annual Effective Dose (Sv)
Dose required to sterilise medical products	25,000 ¹¹
Typical total radiotherapy dose to cancer tumour	60 ¹¹
50% survival probability, whole body dose	4 ¹¹
Employee's dose limit (whole body)	0.02 ¹²
Average annual dose from all sources in Cornwall	0.008 ¹¹
Average annual dose from total natural radiation	0.0026 ¹¹
Average annual dose from radon	0.0013 ¹¹ [19, 4]
Range of ID from exposure to radon in drinking water in UK	10 ⁻⁵ - 10 ⁻³ [20, 21]
Maximum ID from exposure to radon in drinking water in Finland	0.00324 [22]

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 ($ID_{\text{ingestion}}$) can be calculated using the following equation^{13, 14}:

$$ID_{\text{ingestion}} = \text{Conversion}_{\text{ingestion}} \times \text{Consumption}_{\text{tap water}} \times \text{Radon}_{\text{tap water}} \quad \text{Eq. (1)}$$

where,

$\text{Conversion}_{\text{ingestion}}$: conversion factor of committed effective dose from ingestion of radon in water equal to 3.5×10^{-8} Sv/Bq for adults [8,10] or 1.0×10^{-8} [8];

$\text{Consumption}_{\text{tap water}}$: average annual consumption of water;

$\text{Radon}_{\text{tap water}}$: average radon concentration in drinking water.

UNSCEAR¹⁴ has also recommended a conversion factor for the ID from the radon emanating from tap water and then inhaled ($ID_{\text{inhalation}}$). This can be calculated using the following equation:

$$ID_{\text{inhalation}} = \text{Conversion}_{\text{inhalation}} \times \text{Radon}_{\text{tap water}} \times \text{Transfer}_{\text{water to air}} \times F_{\text{radon to progeny}} \times T_{\text{indoors}} \quad \text{Eq. (2)}$$

where,

$\text{Conversion}_{\text{inhalation}}$: conversion factor of committed effective dose from inhalation of waterborne radon equal to 9×10^{-9} Sv/Bq¹⁴;

$\text{Radon}_{\text{tap water}}$: annual average radon concentration in drinking water;

$\text{Transfer}_{\text{water to air}}$: Radon transfer coefficient from tap water to air, equal to 0.1 l/m^3 (1.0×10^{-4});

$F_{\text{radon to progeny}}$: 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 ($ID_{\text{indoor radon}}$), can be calculated using the following equation¹⁴:

$$ID_{\text{indoor radon}} = \text{Conversion}_{\text{inhalation}} \times \text{Radon}_{\text{indoor air}} \times \text{Transfer}_{\text{water to air}} \times F_{\text{radon to progeny}} \times T_{\text{indoors}} \quad \text{Eq. (3)}$$

where,

$\text{Radon}_{\text{indoor air}}$: annual average radon concentration in indoor air;

$\text{Conversion}_{\text{inhalation}}$, $\text{Transfer}_{\text{water to air}}$, $F_{\text{radon to progeny}}$, and T_{indoors} as in Eq (2).

Using Eq. (1), (2) and (3) for a range of $\text{Radon}_{\text{tap water}}$ and $\text{Radon}_{\text{indoor air}}$ values, we can estimate $ID_{\text{ingestion}}$, $ID_{\text{inhalation}}$, and $ID_{\text{indoor radon}}$ for adults, for different scenarios of radon contamination of drinking water and indoor air, and for different regulatory frameworks (Table 4).

¹¹ <http://www.npl.co.uk/educate-explore/factsheets/ionising-radiation/>

¹² <http://www.hse.gov.uk/radiation/ionising/doses/>

¹³ www.ilo.org/...protect/---.../---safework/.../publication/wcms_171036.pdf

¹⁴ www.unscear.org/docs/reports/annexb.pdf

Table 4. Summary of ID values from ingestion and inhalation of waterborne radon corresponding to for a range of radon concentrations in drinking water¹⁵.

Exposure to radon in drinking water	Radon in drinking water (Bq/l)						
	11 US EPA parametric value	100 EU min. parametric value	148 US EPA Action Level	200	400	800	1000 EU Action Level
ID _{ingestion} (mSv/y)	0.02	0.18	0.3	0.4	0.7	1.4	1.8
ID _{inhalation} (mSv/y)	0.03	0.25	0.4	0.5	1.0	2.0	2.5
ID _{waterborne radon} (mSv/y)	0.05	0.43	0.63	0.85	1.71	3.42	4.27

Exposure to radon in indoor air	Radon in indoor air (Bq/m ³)						
	100 UK Target Level	148 US Action Level	200 UK Action Level	400	600	800	1000
ID _{indoor radon} (mSv/y)	2.52	3.73	5.04	10.08	15.12	17.64	20.16

¹⁵ Conversion_{ingestion}=3.5 X 10⁻⁸; 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 4 shows that:

- ID due to inhalation of radon released from tap water is almost twice as high as the ID due to ingestion of radon-contaminated tap water.
- The levels required for remedial action are strikingly different between the USA and EU. In particular, 148 Bq/l is the US Action level for multimedia (i.e. from all sources) mitigation of residential radon; by contrast, 1000 Bq/l is the Directive's recommendation for mitigation of radon only in drinking water supplies.
- Similar annual effective doses are caused by exposure to water containing 1000 Bq/l radon and indoor radon concentration of 200 Bq/m³, which is the Action Level established in Recommendation 90/143/Euratom [16] and Europe [23]; and endorsed by the HPA in Scotland.

5.3 What are the practices that increase exposure to radon in drinking water?

Radon can be high in tap water that is freshly drawn from contaminated groundwater supplies. In this case it can also contaminate indoor air. A commonly used estimate for the transfer coefficient of radon between tap water and indoor air is 1.0×10^{-4} [24; 25; 26], i.e. for every 1 Bq/l of radon in tap water an increase by 0.1 Bq/m³ of radon in indoor air is expected. This, however, depends on lifestyle: high indoor temperature, poor home ventilation, and heating or agitation of water before use (e.g. cooking, showering, and laundering) significantly increase radon degassing out of the water [4].

5.4 What does research show about the radon content of drinking water in Scotland?

Currently only two research articles, both published in 1993, present and discuss radon concentrations in drinking water in Scotland [27, 28]. The major driver for these studies has been (i) the increasing awareness of radon as a geogenic hazard based on studies in the USA, e.g. [24]; (ii) the development of radon-in-air portable detectors; and (iii) advances in scintillation counting technology, which enabled the analyses. The survey carried out by Allen et al. [27] presents radon concentrations in the tap water of 800 schools in the UK, several of them in areas of Scotland known to have relatively high background variations due to the occurrence of naturally occurring radioactive materials (NORMs) (Table 5). Similarly, Al-Doorie et al. [28] describe radon concentrations in the tap water from 70 private wells located in two contrasting, in terms of their NORM content, types of rock (i.e. igneous granite rock versus meta-sedimentary rock) in the Aberdeen area (Table 5).

The two studies carried out in Scotland clearly show that radon concentrations are well below the minimum parametric value specified in the Directive (Table 5). In addition, the well-survey in the area of Aberdeen gives an assessment of ID due to ingestion and inhalation of the radon escaping from tap water at only 1-5% of the total dose from radon in the atmosphere. However, these surveys do not represent the full range of sources of water, water storage conditions, and types of water supplies in Scotland. The well-survey does not specify whether the conditions under which the water is stored before arriving at the tap is representative of the conditions across Scotland; the school survey does not identify sources of water supply i.e. surface vs groundwater, number of schools, or ID [27]. In addition, these surveys give little or no evidence on the underlying geology. Therefore, although this evidence is reliable, it is not sufficient to help assess areas of likely high exposure to radon in drinking water in Scotland.

Table 5. Radon concentrations in tap water in selected areas in Scotland.

Area	Type of sample	Radon concentrations (min - max)
Dumfries and Galloway	Tap water (School)	0.7 – 71.1 [27]
Grampian	Tap water (School)	0.6 – 62.2 [27]
Highland	Tap water (School)	0.7 – 1.6 [27]
Orkney	Tap water (School)	0.7 [27]
Area of Aberdeen (igneous rock)	Tap water (private well)	40 – 76 [28]
Area of Aberdeen (meta-sedimentary rock)	Tap water (private well)	3 – 35 [28]

5.5 What are the hydrogeological controls on radon concentrations in drinking water?

Radon and radon progeny occurrences are controlled by the underlying geology (Figure 2, Table 6). Radon gas is a radioactive progeny in the decay chain of radium, which in turn is derived from the radioactive decay-chain of uranium-238. Radon can be released to the groundwater or surface waters through erosion and dissolution of uranium-rich rocks [29, 30, 22, 15, 16, 31], or radioactive waste produced from natural gas extraction, water treatment, and mining. However, several studies have shown a poor correlation between uranium in bedrock and radon in associated groundwater [31, 32; 33, 34]. This is because radon and uranium have very different transport behaviours and may therefore have different distributions: radon is an inert gas, whereas uranium is sensitive to subtle changes in redox in groundwater and can thus be precipitated through mineralisation [31].

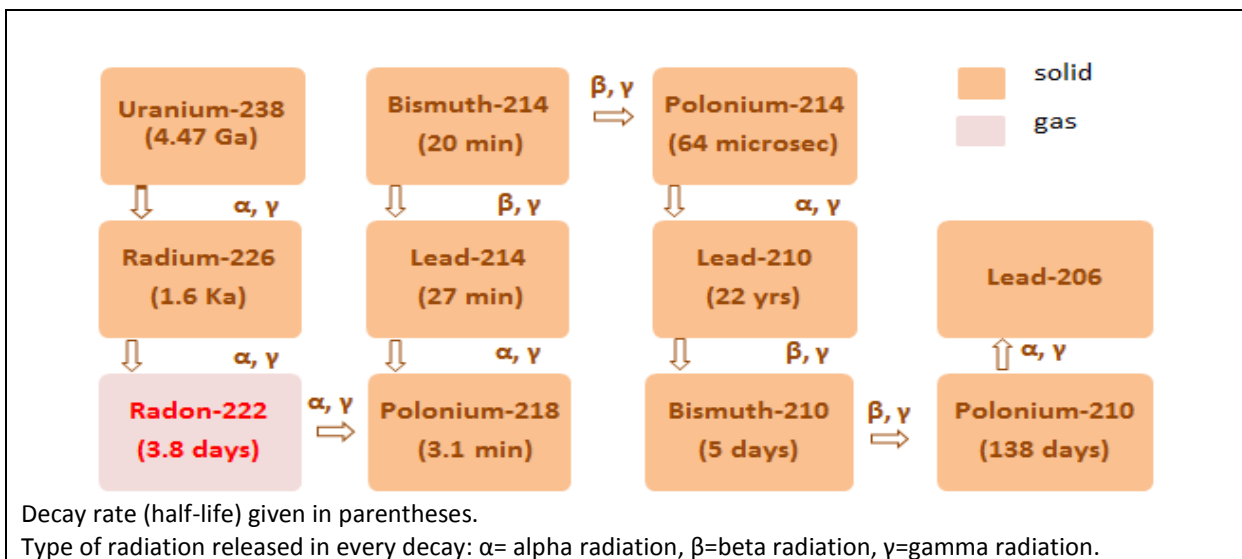


Figure 2. Uranium decay chain and radon progeny.

Due to degassing, radon attains much lower concentrations in surface waters than in groundwater, where it can exceed 80,000 Bq/l [35]. Its solubility in water decreases rapidly with increases in temperature but this is more relevant to domestic uses of drinking water (e.g. cooking, bathing) rather than to conditions in the field [3]. Radon is mainly released into the atmosphere via emanation from permeable soils and fractured rocks; it can also be drawn into buildings through gaps and cracks in solid floors, walls, and service pipes below construction level. Thus, radon in indoor air is commonly used as a proxy for radon in soil or bedrock [36, 4]. This, however, is also controlled by building characteristics and the degree of ventilation [4]. Radon concentrations in outdoor air in the UK are generally low, on average 4 Bq/m³, whilst radon in indoor air in UK dwellings is on average 20 Bq/m³.

Table 6. Geological controls on radon occurrence and concentrations in groundwater.

Underlying Geology	Radon in water (Bq/l)	Reference
Seawater	<2	37
Surface freshwater	<4	37, 38
Springs	50 – 740	39, 40
Wells dug in soil	normal: 10-300	37
	granite 40-400	47
Wells in sedimentary rock	normal: 10-50 (rarely 150)	28, 37, 41
	metamorphic terrain:	42, 43; 44, 45
Wells in crystalline rock	U-poor: 50-500	37
	U-rich granites 300-4,000 (max=63,000)	30, 46
	U rich permatites: max=30,000	37
U-ores	2,000-100,000	30, 37
Wells in granite bedrock	10-42,000	47, 48, 22, 49, 41
Boreholes in granite bedrock	Max=80,000	22, 35
Public water supplies in granite-rich areas	Max=1630	22

At equilibrium, and assuming a radium level at 40 Bq/kg, which is the world-wide average in the earth's crust, the average radon level outdoors is 5 Bq/m³ [38, 16].

Considerable local radon variations may exist within the same rock formations, reflecting local, small-scale, hydrogeological processes (Table 7). Higher radon content is expected in groundwaters where contact with minerals of uranium-rich source material is enhanced, and where emanation, transport, or dilution is restricted. The fraction remaining in solution also depends on the distance radon travels before reaching permeable soils and before decay. Although radon can move rather freely within groundwater, the reported diffusion length is about 10 cm in water and 300 cm in air [50]. Therefore, radon in solution will migrate more quickly in areas of permeable, fractured and fissured rocks than in low-permeability soils with high moisture content [4].

The key message is that high or higher radon levels in drinking water supplies are expected in:

- Areas with uranium-bearing bedrock and associated soils;
- Groundwater rather than in surface waters;
- Areas with impermeable soils and confined aquifers;
- Lowland areas; and
- Areas with high radon in indoor air.

Table 7. Hydrogeological variables affecting radon concentrations in groundwater.

Mechanism increasing radon in groundwater	Hydro-geological variable	Radon levels in groundwater	Reference
Restricting permeability – aeration – dilution with rainwater - recharge	Aquifer type	Confined > unconfined	24, 41, 51; 54; 53 55,52
	Type of soil	Clay > gravel	
	Porosity	Low porosity > high porosity	
	Flow distribution	Low flow > high flow	
	Well use	Irregular > regular	
	Land use	No effect	
Increasing downward (hydraulic) transport	Well altitude	Low altitude > high altitude	37, 41, 56, 57
	Well depth	Varies (aquifer and soil type)	
Increasing surface area of the source U-rich rock with water	Drilling frequency	High frequency > Low frequency	53, 4, 41
	Fractures-imperfections	More > fewer imperfections	
	Distance from fracture zone	Varies	

6. Risk Map for radon in groundwater in Scotland

6.1 Where are the radon affected areas in Scotland?

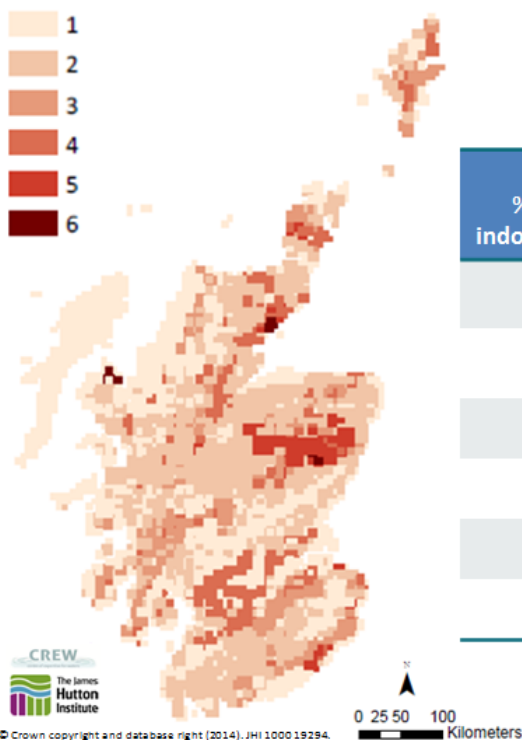
The available evidence [27, 28] suggests that radon concentrations in drinking water in Scotland are much lower than in other parts of the world with similar underlying geology. This evidence comes from only a few sites, however. There is a need to model radon occurrence by identifying the relationship between radon in groundwater and ‘what earth delivers’ in terms of radon. This quantity, or spatial variable, gives the geogenic radon potential [36]. The ‘Indicative Atlas of Radon in Scotland’ (hereafter reported as the Atlas) jointly produced by HPA-BGS [58, 59] is based on this approach. Radon potential is the probability that a home that has not had a radon measurement will have a long-term average radon concentration at or above the radon Action Level, which in the UK is 200 Bq/m³.

The Atlas is based on the results of measurements of radon in over 19,000 homes and interpolation (inverse weighting) within predefined geological units at a 1:50,000 scale [59]. Figure 3 shows a 5-km grid of squares of radon affected areas, i.e. areas with 1% or greater probability of exceeding the UK Action Level of radon in indoor air due to the underlying geology¹⁶ [58,59]. The radon affected areas with more than 10% of homes at or above Action Level for indoor air radon include (Figure 3):

- the Siluro-Devonian uranium-rich granites of Aberdeenshire (Grampian) and Helmsdale area (Highlands), and
- Middle Old Red Sandstone in the Orkney Islands and Caithness (Highlands).

Radon affected areas in Scotland

Radon potential class on a 5 km grid



Radon potential: % of homes with radon in indoor air at or above 200 Bq/m ³	Radon potential class	Risk Level
< 1 %	1	Low
1 - 3 %	2	Medium
3 - 5 %	3	Medium
5 - 10 %	4	Medium
10 - 30 %	5	High
> 30 %	6	High

Figure 3. Radon potential classification in Scotland. The radon potential ArcGIS shapefile, provided by BGS (Appendix 1), had been intersected with the British National Grid 5 km tile boundaries; classification is based on selecting the highest radon potential class (1-6) that occurred within each 5-km square. Data source: BGS/HPA. © Crown copyright and database right (2014). James Hutton Institute 1000 19294.

¹⁶ www.ukradon.org

In addition, rock formations associated with elevated, compared with average, radon levels in indoor air are granitic bedrock and U-mineralisation and are found in (Figure 3):

- Dalradian-Carboniferous limestones throughout Scotland
- Ordovician-Silurian greywackes throughout Scotland
- Late Jurassic mudstones, siltstones and sandstones on the north-east coast
- Devonian lavas and tuffs at the Cheviot granites
- Dalradian metasedimentary rocks in the Shetlands
- Unconsolidated deposits in the Southern Uplands and the Argyll area

6.2 What are the caveats of using the Atlas to identify risk areas for radon in groundwater?

- (i) Radon potential does not account for heterogeneity in groundwater flow patterns within the same geological unit, thus it may not be suitable for aquifers with high and variable flow patterns, high recharge rates, or high drilling or abstraction frequency. However, in most of these cases, radon concentration is expected to be lower, therefore uncertainties in radon distribution are counteracted by the lower risk of elevated values.
- (ii) Uranium mineral precipitation in bedrock with low uranium content may cause a mismatch between underlying geology, radon potential, and radon in groundwater.
- (iii) Distribution of radon in indoor air within the affected areas is highly variable. For example, in Aberdeenshire and the Orkneys, average levels of radon in indoor air are about 150 Bq/m³ but maximum values exceed 6000 Bq/m³ [60].
- (iv) The information in each 5-km square is indicative, i.e. each grid is characterised by the highest radon potential found within it. This means that a home within a square with high radon potential may not have high radon in indoor air; it follows that it may not have high radon in tap water drawn from groundwater supplies.
- (v) The output is based on, and limited to, an interpretation of the records in the possession of BGS and HPA at the time the base radon indoor air measurements were taken, i.e. 2008 for Scotland [61]. However, assuming that there have not been drastic changes in building materials or density of dwellings, the currently available radon potential map provides unique information about 'what earth delivers' in terms of radon. In this context, it could help predict areas of likely high exposure to radon in drinking water in Scotland and target baseline surveys to obtain more information.

6.3 Where are the 'areas of likely high exposure' to radon in groundwater in Scotland?

Identification of 'areas of likely high exposure' to radon in drinking water is based on two assumptions supported by the evidence collected from regulatory datasets and peer-reviewed literature:

- (i) Risk of elevated radon concentrations in the tap water coming from surface public or private drinking water supplies is minimal.
- (ii) Radon in the groundwater beneath a home and radon in its indoor air share the same geological source. Therefore, if a water supply is within a grid square at or above 5% radon potential, then all water supplies sharing the same groundwater waterbody will be at risk of elevated radon concentrations.

Creating the risk map for a High Risk Area and alternative Risk Area scenarios for radon in groundwater involves the steps described in Appendix II. The single most important criterion for selecting a groundwater body in each scenario is that it intersects at least one square of known class (high or medium) of radon potential (Table 8). This addresses the spatial heterogeneity in radon potential as each Risk Area scenario includes a variety of radon potential classes. It also addresses uncertainties in linking radon potential in indoor air with radon in groundwater.

Table 8. Scenarios for Risk Area in relation to radon potential class.

Radon potential class	Scenario for Risk Area
≥5	High Risk Area
≥4	Scenario 1 (or Medium plus High Risk Area)
≥3	Scenario 2
≥2	Scenario 3

The High Risk Area is intended to show ‘areas of likely high exposure’ to radon in groundwater public and private drinking water supplies (Figure 4). This is in line with the new Directive’s requirement for monitoring. The High Risk Area mainly includes groundwater bodies in the areas of Aberdeenshire (Grampian), the Highlands, and the Orkney Islands.

Scenarios 1, 2 and 3, are explored to inform DWQR whether there are additional areas where water supplies could have elevated radon concentrations (Figure 5). These alternative scenarios increase dramatically the area of likely exposure to radon in drinking water (Figure 7). However, given the coarse resolution of the Atlas and the relatively low number of homes at risk of being at or above Action Level in Options 1, 2, and 3, the alternative scenarios add uncertainties rather than information on likely high exposure to radon.

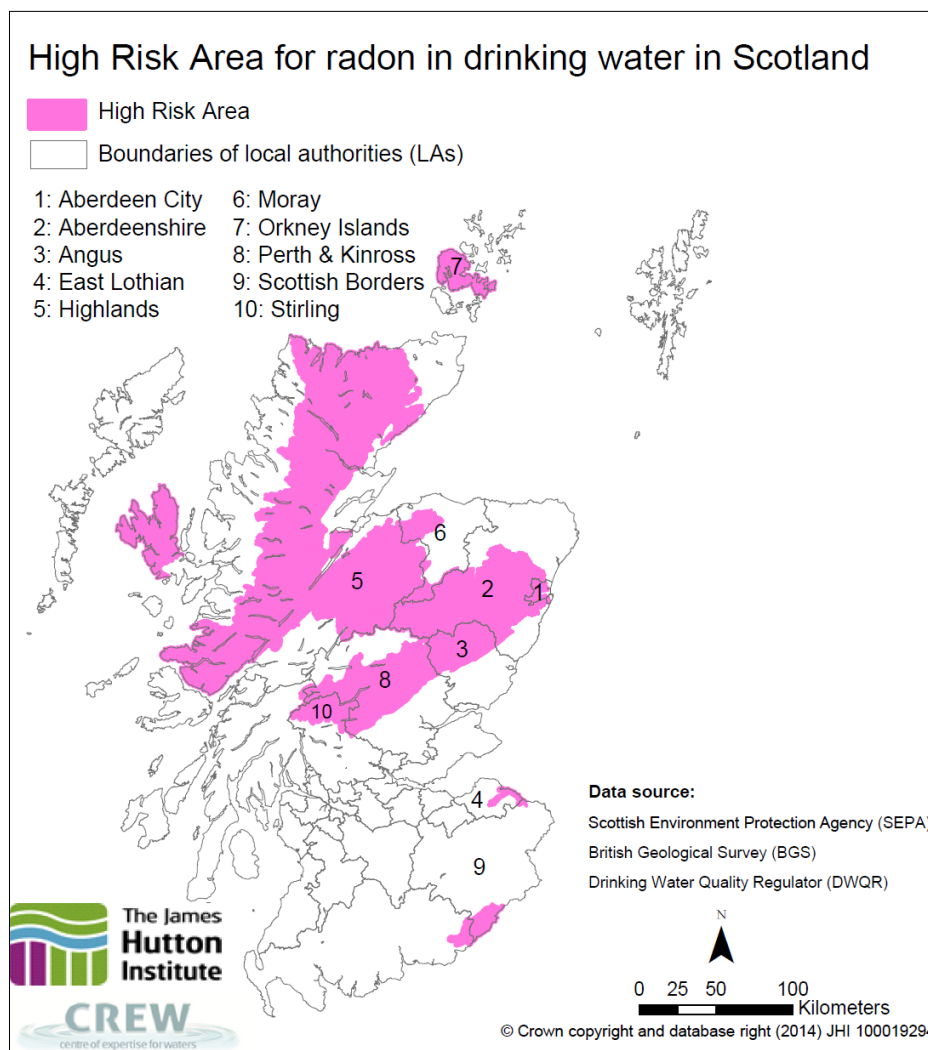
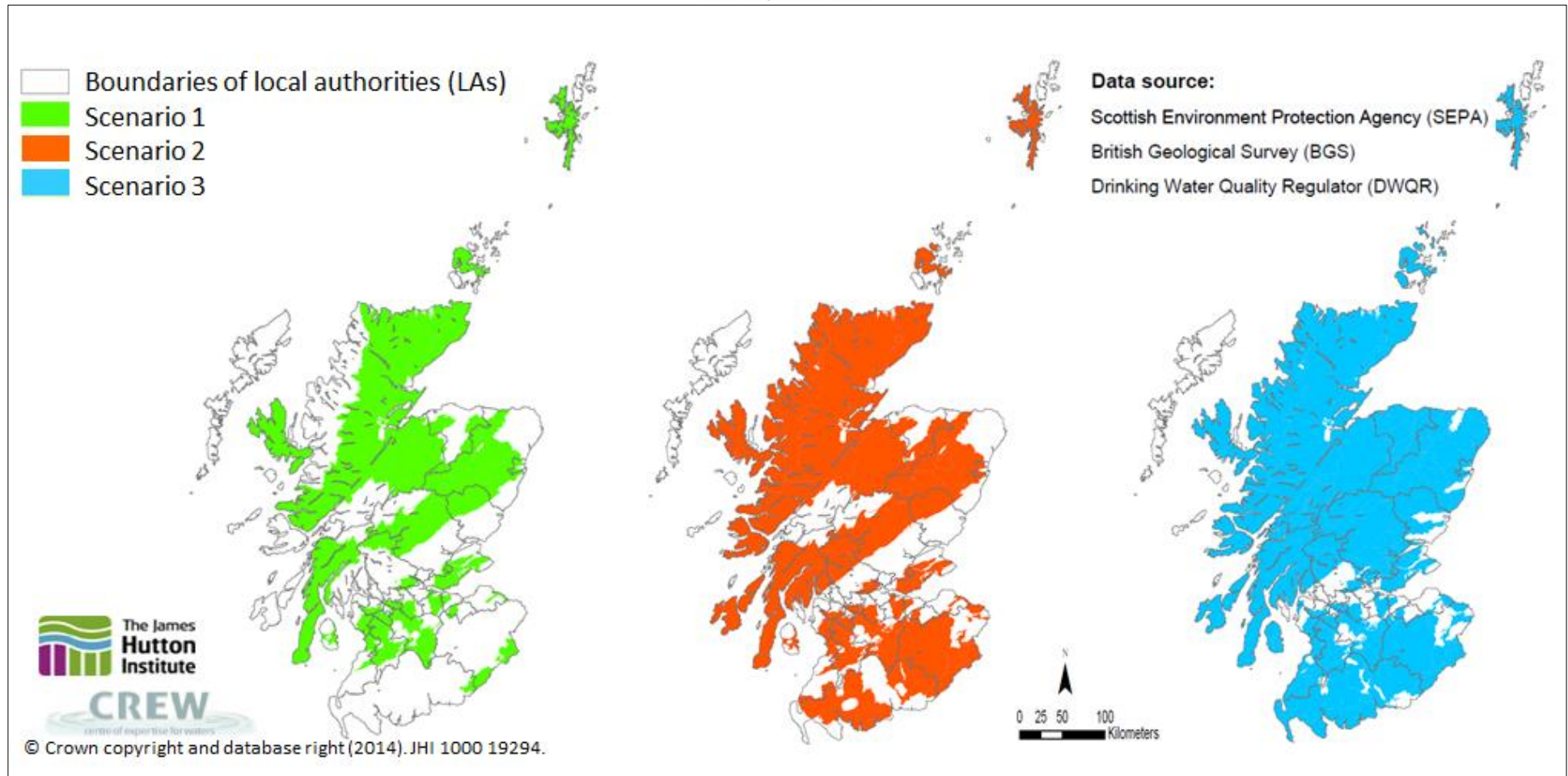


Figure 4. Map of groundwater bodies at risk of high radon content in Scotland showing the High Risk Area within each local authority.



The maps show Risk Areas within each local authority (LA) in each scenario.

Figure 7. Alternative Risk Area scenarios for radon in groundwater.

6.4 How many water supplies are found in each Risk Area scenario?

The number of water supplies within the Risk Area gradually increases from 477 in the High Risk Area to 1479 in Scenario 3 (Table 9). The greatest increase is in the number of private water supplies. The High Risk Area includes 31% of all public groundwater supplies (Figures 5) and 33% of all private boreholes, 30% of all springs and 24% of all private wells (Figure 6). In addition, ten of the 32 local authorities have a part of the High Risk Area under their jurisdiction (Table 10). On the other hand, the number of local authorities with a Risk Area rises to 22, 23 and 26 in Scenarios 1, 2, and 3, respectively (Table 10). The greatest increase in the number of supplies is in the number of private springs (Table 10).

Table 9. Comparative presentation of numbers of groundwater public and type A-PWS in each Risk Area scenario.

Scenario for Risk Area	No. of public groundwater supplies within Risk Area	No. of type A-PWS groundwater supplies within Risk Area
Suggested Risk Area	24	453
Option 1	40	739
Option 2	53	1102
Option 3	67	1412
All Scotland	77	1497

Data source: DWQR.

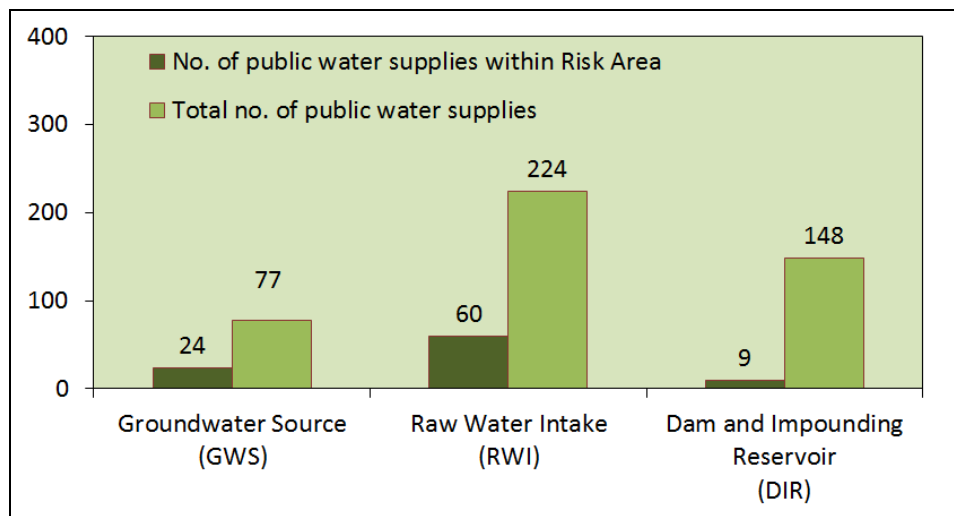


Figure 5. Number of public water supplies within and outwith the High Risk Area

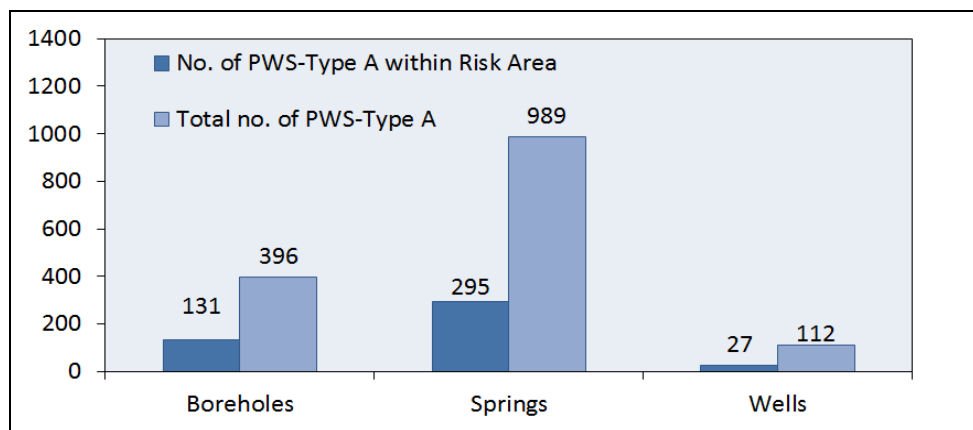


Figure 6. Number of type A – private water supplies (PWS) within and outwith the High Risk Area.

Table 9. Number of groundwater type A-PWS in each Risk Area scenario.

Local authority (LA)	Number of type A-PWS using groundwater sources											
	High Risk Area			Scenario 1			Scenario 2			Scenario 3		
	Boreholes	Wells	Springs	Boreholes	Wells	Springs	Boreholes	Wells	Springs	Boreholes	Wells	Springs
Aberdeen City	0	1	0	0	1	0	0	1	0	0	1	1
Aberdeenshire	16	12	80	21	22	101	21	22	101	31	36	125
Angus	4	1	16	4	1	16	4	1	16	9	1	20
East Lothian	1	0	3	1	0	3	1	0	4	2	0	4
Highland	67	5	113	82	6	143	95	7	160	101	8	173
Moray	2	3	9	2	3	18	2	4	36	10	8	78
Orkney	4	2	2	4	2	2	10	3	3	17	3	4
Perth & Kinross	32	3	54	35	4	58	35	4	58	59	6	93
Scottish Borders	2	-	12	2	0	21	20	1	96	21	1	97
Stirling	3	-	6	3	0	8	5	0	12	5	0	13
Argyll and Bute	-	-	-	4	1	84	28	6	147	33	8	163
E. Renfrewshire	-	-	-	4	1	1	4	1	1	4	1	1
Falkirk	-	-	-	1	0	0	1	0	0	1	0	0
Fife	-	-	-	12	0	9	12	0	9	18	0	16
North Ayrshire	-	-	-	4	1	7	4	1	7	4	1	12
Renfrewshire	-	-	-	1	1	0	1	1	0	1	1	0
Shetland	-	-	-	0	1	0	0	1	0	0	1	0
S. Ayrshire	-	-	-	1	0	3	1	0	4	6	0	14
S. Lanarkshire	-	-	-	6	0	10	7	0	15	7	0	15
West Lothian	-	-	-	2	1	3	2	1	4	2	1	4
Dumfries & Galloway	-	-	-	-	-	-	16	17	70	27	23	94
Clackmannanshire	-	-	-	-	-	-	-	-	-	2	1	2
Dundee City	-	-	-	-	-	-	-	-	-	1	0	0
Inverclyde	-	-	-	-	-	-	-	-	-	0	0	2

7. What can policy-makers do about this?

7.1 Reflecting on policies on radon in drinking water in other countries

Among European countries, only Finland, Sweden, the Czech Republic, Romania, Russia, and the Slovak Republic have established parametric values for radon in drinking water. The present limits are within the range for 50-500 Bq/l for public water supplies and 120-1000 Bq/l for private water supplies [62]. A common characteristic justifying the specified parametric levels in these countries is that a large number of water supplies draw water from wells drilled into crystalline bedrock, often granites enriched in uranium. Several thousand wells containing water with radon concentration levels above 1000 Bq/l, and several wells with levels greater than 20,000 Bq/l have been found [62]. It remains to be explored whether wells, springs and boreholes in the High Risk Area identified in the current report, that includes groundwater bodies on granite rock, are radon-contaminated.

In the USA, supplies serving 25 people or more are considered to be public water supplies. The Action Level for radon in drinking water is at 148 Bq/l combined with requirements for multimedia mitigation (MMM) programs to address radon that enters indoor air from soil under homes and buildings.¹⁷ This value corresponds to background levels in outdoor air (i.e. about 14 Bq/m³). States that have not adopted such programs are subject to a lower Action Level of 11 Bq/l or home owners are given the option to develop individual local MMM programs and reduce levels in drinking water to 148 Bq/l. It must be mentioned that in consultations with health and State stakeholders concerns have been expressed that a standard for radon in drinking water will mislead the public about the risks of radon in drinking water relative to the greater public health risk of radon in indoor air¹⁶. This is because the Action Level for radon in drinking water is enforceable in the US whereas the Action Level for indoor air is not. This is an important policy issue that should be explored in the context of UK and Scotland.

7.2 What is the best Risk Area scenario?

The Directive requires monitoring of radon in drinking water where evidence suggests that the specified parametric values laid down may be exceeded. Existing reliable evidence is collected in this report. As a result, the High Risk Area and the alternative Risk Area scenarios have been identified to inform policy action and help SW and Scottish local authorities target baseline surveys, radon monitoring, and, if judged appropriate, remedial action. DWQR are currently exploring the cost and feasibility of the radon analysis in supplies at risk of radon contamination in consultation with SW, and whether testing for indoor air radon and for radon in water can be carried out simultaneously. In addition, baseline surveys in early 2015 will allow for identifying the actual range of values in the selected Risk Area scenario. Once this information is compiled, it will substantially help assess the best scenario to ensure value for money in terms of protection of the general public from radon exposure, and compliance with the requirements of the Directive.

Table 11 provides a checklist of strengths and limitations of the Risk Area scenarios based on the current work to help DWQR formulate future action. Scenario selection will substantially influence the way baseline surveys will be conducted. In the case of the High Risk Area being selected, two options for conducting baseline surveys could be considered.

- Option 1 involves comparing radon levels among the High Risk Area and Scenarios 1, 2, and 3 by means of random sampling within each scenario to inform decisions on the range of values and where monitoring or mitigation is required.
- Option 2 involves surveying supplies only within the High Risk Area to inform decisions about whether any sampling for radon is required at all in Scotland. The first option may be more representative in terms of sampling design, although this depends on whether radon is

¹⁷ <http://water.epa.gov/lawsregs/rulesregs/sdwa/radon/regulations.cfm>

elevated in Scenarios 1, 2, and 3 compared with the High Risk Area scenario. However, the second option offers an opportunity to obtain information on the basis of simplicity, feasibility, accessibility, and within the specified timelines for the domestication of the Directive.

Table 11. Strengths and limitations of the Risk Area scenarios in terms of monitoring, feasibility and cost and protection of the general public

Risk Area Scenario	Strengths	Limitations
High Risk Area	<ul style="list-style-type: none"> Representative of high radon potential in line with the Directive's requirement Accessibility by SW and LAs Feasible as it has the lowest number of supplies Radon measurements could be compared to those in other scenarios 	Field measurements are needed to verify that high radon levels are found in this scenario
Scenario 1		<ul style="list-style-type: none"> Inclusion of many areas not easily accessible. Uncertain representativeness of 'likely high exposure' to radon; may be biased towards low exposure as it includes many areas of low radon potential.
Scenario 2	It may ensure greater protection for the population but only if indoor air radon and radon in groundwater are strongly correlated in all combinations of radon potential squares and groundwater bodies	
Scenario 3		<ul style="list-style-type: none"> Needs extra areas and resources without adding information on high radon values in water.

7.3 What are the options for Scottish Water (SW) and the local authorities (LAs)?

Based on the evidence reviewed in the current report it is possible to assess the need for monitoring or baseline surveys to establish whether the specified parametric values and Action Level for radon in water may be exceeded, and under what conditions. Therefore, we recommend that:

- Monitoring is not required in surface water supplies.
- Baseline surveys in public groundwater supplies are optional when residence time of water in treatment plants is long.
- Baseline surveys in public groundwater supplies are required when residence time of water in treatment plants is shorter than radon's half-life, e.g. in small-scale public groundwater supplies. Sampling in this case may be 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, surveys for groundwater public water supplies could be carried out at the treatment works.
- Baseline surveys in type A private water supplies taking water from groundwater sources (wells, boreholes or springs) are required. This will help LAs plan further monitoring, the awareness campaign for mitigation, and remedial action if required. Sampling in this case should be carried out at the point of compliance, i.e. the tap water.
- Seasonal monitoring or baseline surveys are not required.
- Replicate tap water samples from the same distribution network of groundwater private supplies are required, together with recording of number of properties and type of supply, to assess any causes of variation in radon levels and practical radon mitigation methods before the water reaches the home.

- Aligning radon baseline surveys with the monitoring visits in compliance with the PWS regulations is a practical way forward for local authorities.

Synergies with the Scottish Government's policy on protection from exposure to indoor air radon could also be sought. Our approach of identifying a risk area makes this option possible. For example, in response to the publication of the radon potential map, the Scottish Government has announced free testing for homeowners in areas with a five per cent chance or more of houses being above the Action Level for indoor air radon¹⁸. This policy includes all homes within Scenario 1 Risk Area for radon in groundwater and many homes within the High Risk Area identified in this report.

In this context, options for local authorities include:

- Target regulatory monitoring of radon in tap water in homes served by groundwater type A or type B-PWS that have already been tested for indoor air radon within Scenario 1 Risk Area or High Risk Area and have been found to be at or above Action Level;
- Target surveys in all homes served by groundwater Type A-PWS and free testing in groundwater type B-PWS within Scenario 1 Risk Area or the High Risk Area, depending on the decision made on Risk Area scenario; and
- Target awareness for radon mitigation measures in drinking water within Scenario 1 Risk Area or the High Risk Area, depending on the decision made on Risk Area scenario.

7.4 What are the options for Action Level?

Radon and its progeny are not required for the calculation of ID in the new Directive. However, the effective dose from exposure to radon in drinking water must be taken into account to ensure protection of the general public 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/m³ 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]. It must be emphasised, however, that a 5×10^{-5} probability of fatal cancer per mSv of effective dose has been advised for the general public by the International Commission on Radiological Protection [67]; this dose corresponds to the combined exposure, by ingestion and inhalation, to a radon concentration of 230 Bq/l in water, and without considering indoor air radon coming from the ground beneath the home. The Environment Protection Agency in the US (USEPA), on the other hand, estimates that lifetime exposure to drinking water at 148 Bq/l would correspond to an incremental lifetime cancer risk of 26 in 10,000 to the general population; this exceeds the risk range of 1 in 10,000 to 1 in 1 million (10^{-4} to 10^{-6}) traditionally used by USEPA in developing national drinking water standards^{16, 19}.

Since the Action Level of indoor air radon in the UK is at 200 Bq/m³ and exposure to this radon level is similar to exposure by ingestion and inhalation of tap water with 1000 Bq/l of radon, then it is sensible to apply the Directive's recommendation for an Action Level for drinking water at 1000 Bq/l. It is not known how likely it is for a member of the general public to be chronically exposed to both radon in indoor air and in tap water at or near the specified Action Levels. This likelihood and its consequences to public health remain to be explored once field measurements are completed.

7.5 What are the options for a parametric value?

The available options for parametric value are:

- (i) Set a value within the range in the new Directive's recommendations, i.e. between 100 Bq/l and the Action Level value (1000 Bq/l).

¹⁶ <http://water.epa.gov/lawsregs/rulesregs/sdwa/radon/regulations.cfm>

¹⁸ <http://www.scotland.gov.uk/news/releases/2009/04/23101833>

¹⁹ water.epa.gov/lawsregs/rulesregs/sdwa/radon/upload/epa815r12002.pdf

- (ii) Set a value at the lower end of the recommended range
- (iii) Set a value at the upper end of the recommended range.

Laying down a parametric value lower than the Action Level is in line with the International Committee of Radiological Protection's (ICRP) recommendation of the ALARA principle (As Low As Reasonably Achievable) within all radiation protection regulations²⁰. In this option, a relatively low parametric value lowers chronic exposure of the population to radiation from radon in drinking water but compliance is resource intensive, as it would require a higher number of supplies to be monitored and treated to achieve compliance.

Thus, to support decision making on a parametric value for radon in water Scotland it is essential to consider the resources required to:

- Monitor radon in drinking water where evidence suggests that radon levels may be as low as the specified parametric value, e.g. availability of staff and accredited laboratories in SW and LAs, cost of analysis, accessibility, and the number of supplies needing monitoring. Accessibility is very important for LAs as failure to conduct the planned analysis will result in failure to comply with the regulatory requirement.
- Inform home owners of private water supplies about what has to be done to minimise the likelihood of their supply failing to comply with the specified standard.
- Mitigate effectively radon levels in drinking water and monitor the effectiveness of mitigation measures to ensure that parametric values are not exceeded.
- Ensure that mitigation of radon in water is a cost-effective approach towards protecting the population from the hazards of radon exposure.

The level of a parametric value is clearly connected to what mitigation measures are achievable. From a feasibility standpoint, groundwater in public water treatment plants most likely already undergoes a process that allows for effective mitigation of radon before it enters the distribution network. However, this must be verified with measurements and in consultation with SW.

On the other hand, radon mitigation in private water supplies may implicate financial incentives (e.g. devices that mitigate radon before it arrives at the tap water or at the tap water), or enforcement, and investment of resources in raising public awareness of hazards and safe mitigation practices.

Radon problems in private groundwater supplies can be fixed in two ways²¹:

- (i) Point of entry treatment to remove radon from the water before it reaches the tap; granular activated carbon (GAC) filters or aeration devices could be used. While GAC filters usually cost less than aeration devices they can collect radioactivity and may require a special method of disposal.
- (ii) Point of use treatment devices remove radon from tap water, but treat only a small portion of water used in a home, e.g. a glass of water.

Selecting one of the options available for a parametric value should also take into account the far greater risk from exposure to radon in the indoor air. Thus, investment of resources (e.g. financial, staff time, maintenance) to mitigate radon in water to comply with a parametric value near the lower end of the range in the Directive's recommendations 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 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 target monitoring and action where risk to public health is evidenced by epidemiological findings. In this approach, it is reasonable to assume that a single standard for a parametric value and Action Level

²⁰ http://ec.europa.eu/health/scientific_committees/opinions_layman/security-scanners/en/l-3/2-radiation-protection.htm

²¹ <http://enhs.umn.edu/hazards/hazardssite/radon/radonprevention.html>

would help communicate a clear message to the public about the need for mitigation at levels below the specified standard, and for remedial action in cases where the standard is exceeded.

The options for parametric value will be analysed specifically in the follow-up project in the light of evidence from radon measurements within the selected Risk Area, the analysis of required resources for radon monitoring and mitigation, and the output of the surveys conducted by the DWI in England and Wales.

8. Concluding remarks

This report collates existing evidence to inform DWQR about the implications for Scotland of the provisions and scope of the Directive. It offers information and criteria to help select the most practical option to implement the Directive's recommendations on a parametric value for radon. It also analyses the causes and health implications of radon in drinking water and describes radon affected areas from a groundwater perspective in Scotland. The recommendations based on this report will help target representative surveys and action in preparation for the transposition of the Directive into Scottish legislation by November 2015.

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Glossary

'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]

'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]

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.

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

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.

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.

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. In ICRP publication 60, radiation detriment is developed and used to derived Dose Limits.

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 3×10^{15} hertz or more capable of producing ions directly or indirectly'.

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

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

Appendix

Appendix I: Steps followed to produce the Indicative Atlas of Radon in Scotland (Miles et al., 2011)

Radon potential was mapped using the integrated geological/grid square method, which is described in detail by Miles and Appleton (2005):

- (i) Each combination of 446 geological units (simplified from 4,800 bedrock and 189 superficial units) found in Scotland is taken in turn, and the spatial variation of radon potential within each combination is mapped;
- (ii) The combination is treated as if it was continuous over the land area (Scheib et al, 2009). The named geological units are attributed to the radon measurements from each house location using the BGS 1:50,000 scale DiGMapGB digital data;
- (iii) Each 5-km grid square is coloured according to the highest radon potential found within it.

Appendix II: Steps followed to identify Risk Area scenarios for radon in groundwater

Data sources

1. The locations (site reference) and source of water of public and type A-private water supplies in Scotland, provided by the DWQR.
2. The groundwater waterbody boundaries, jointly produced by SEPA and BGS. This map is created from main river catchment boundaries and some linework from the BGS 1:250,000 solid geology dataset produced to inform the delineation of groundwater waterbodies in Scotland in line with the provisions of the Water Framework Directive (Figure II.1)
3. The 5km grid square of the Indicative Atlas of Radon in Scotland described in Appendix I.

Creating a map of 'areas of likely high exposure' to radon in drinking water using ArcGIS involves:

1. Matching locations of groundwater supplies ('supplies' layer) with the groundwater waterbodies ('hydro' layer, Figure II.1) to create the 'supplies-hydro' layer.
2. Joining the 'supplies-hydro' layer with radon potential map ('geology' layer, Figure II.1) to create the 'supplies-hydro-geology' layer.
3. Selecting supply-points from the 'supplies-hydro-geology' layer from a certain radon potential class, depending on Risk Area scenario.
 - For High Risk Area scenario we select supplies from class >5
 - For Scenario 1 we select supplies from class >4
 - For Scenario 2 we select supplies from class >3
 - For Scenario 3 we select supplies from class >2

Then for each scenario:

4. Using the selected features at Step 3 to intersect the 'hydro' layer to produce the 'groundwater' layer for each Risk Area scenario.
5. Steps 1 to 4 are done separately for public and private water supplies. Then we join the 'groundwater' layer of public and the private supplies. This combined area is the final Risk Area for each scenario.

The final output, which accompanies the current report, includes:

- (i) A polygon shapefile for each Risk Area scenario.
- (ii) A point shapefile of public supplies for each Risk Area scenario.
- (iv) A point shapefile of type A-private water supplies for each Risk Area scenario.

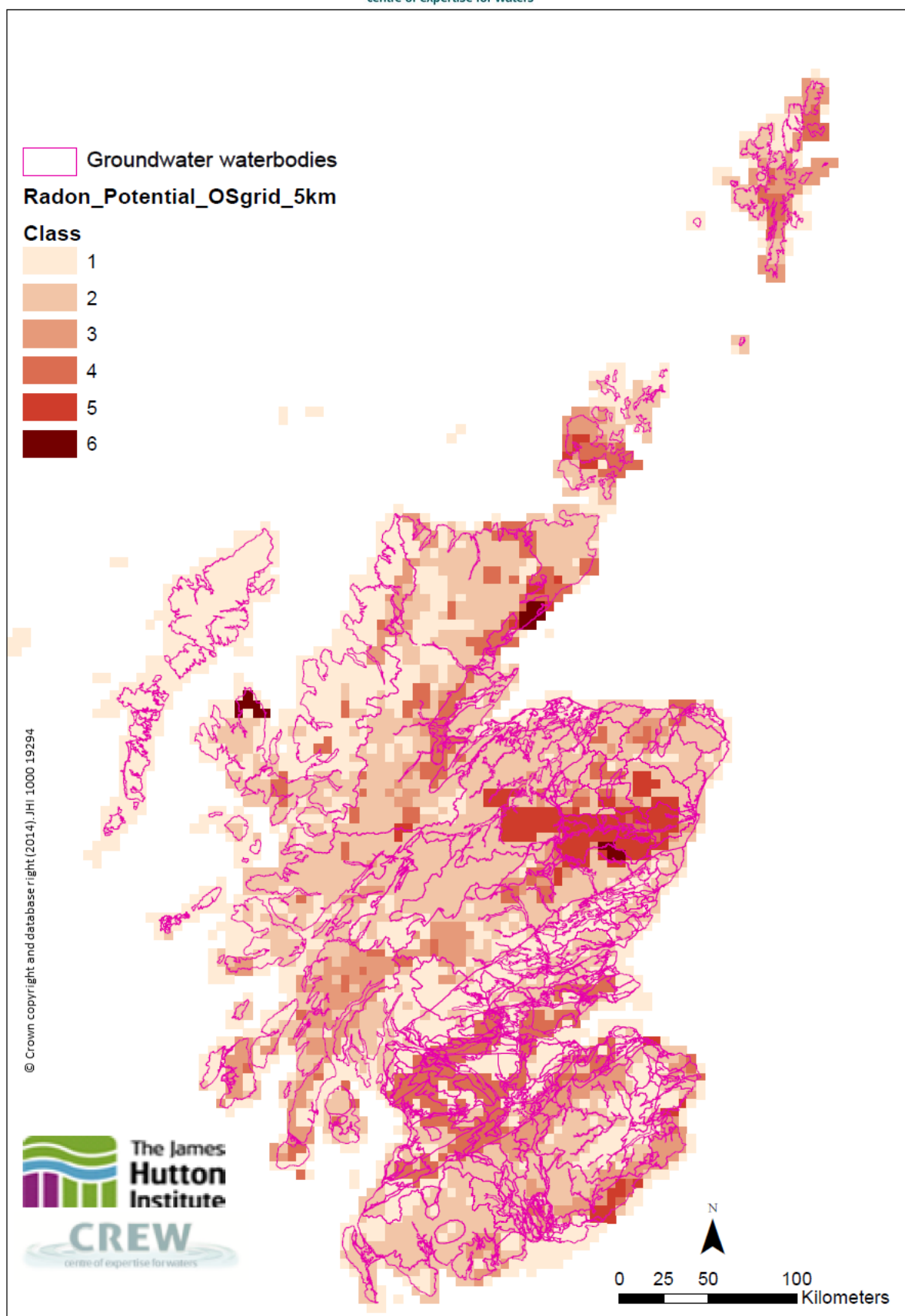


Figure II.1. Groundwater bodies ('hydro' layer) overlain on the radon potential grid square ('geology' layer).



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