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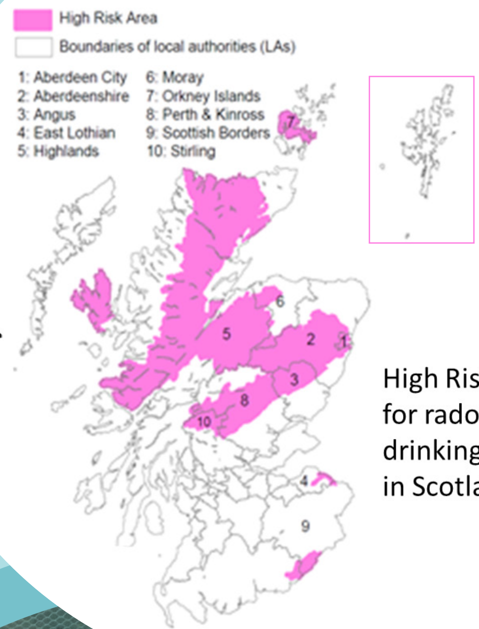
Water quality and radon: Implications for Scotland of the provisions and scope of the Council Directive 2013/51/Euratom for radon in drinking water



High Risk Areas for radon in drinking water in Scotland

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Abbreviations

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

Elements

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

Contents

Executive Summary

The Questions

What is the range of radon concentrations in drinking water in Scotland? What is the influence of the underlying rock or soil, hydrology, and water supply type on radon in drinking water? Where could be the areas of likely high exposure to radon in drinking water in Scotland?

Key findings

1. Radon (222Rn) 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 (i.e. the time required for one half of a given concentration of radon to decay) of 3.8 days. The radioactive products of its decay chain (radon progeny) are all solid and also give off radiation, either alpha and gamma radiation (i.e. polonium) or beta and gamma radiation (i.e. lead and bismuth).

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

- By ingestion of radon-contaminated groundwater before radon degassing to indoor-air.

- 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 but the health risk due to inhalation of radon emanating from tap water is almost twice as high as the health risk due to ingestion of radon-contaminated drinking water.

- By inhalation of the radon progeny that may cling on dust particles found in the indoor-air.

3. There is limited evidence on radon levels in 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.

4. Radon occurrence in drinking water is controlled by underlying geology, hydrological processes influencing groundwater, water supply type, indoor conditions, and domestic uses of water.

- Higher radon concentrations are expected in areas underlain by uranium-bearing bedrock and associated soils. In Scotland, such areas are found in Aberdeenshire, Helmsdale, the Orkney Islands, the Southern Uplands, the Argyll area, and in limestone throughout the country.

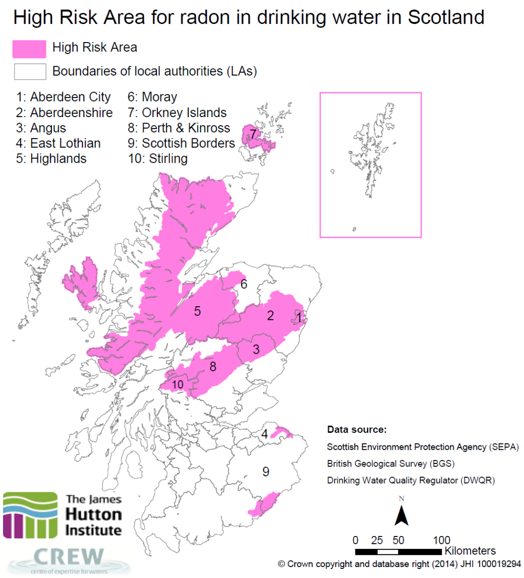
- High radon concentrations are associated with groundwater rather than surface waters and especially with groundwater bodies that are subject to frequent drilling and restricted radon degassing, water transport or dilution with rainfall.

- There is higher risk of exposure to radon in drinking water from small private or public supplies than from large public water supplies. Public water supplies come to households via large storage systems with long residence times that allow radon to escape into the air or decay to very low levels before reaching the consumer. By contrast, the time between pumping and consumption of water from small private water supplies or small public networks, is well within radon's half-time.

- High indoor-air temperature and heating or agitation of water before use increase radon degassing out of water.

5. The high-risk area for radon in drinking water refers to the area presenting the highest risk of exposure to radon in drinking water and includes 24 out of 77 public supplies and 453 out of 1497 type A-private groundwater drinking water supplies in 10 out of 32 local authorities (see map).

6. Three alternative scenarios for risk areas for radon in groundwater can be identified to include areas with medium and low risk of exposure to radon in drinking water. However, these alternative scenarios add uncertainties rather than information on likely high exposure to radon.



Map showing the proposed high-risk area for exposure to radon in drinking water.

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 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 in 'areas of likely high exposure' to radon in drinking water, where representative surveys, or other reliable information, indicate that the radon parametric value is exceeded, or likely to be exceeded. Member States must ensure that non-compliances are immediately investigated for their potential to pose risk to human health. The Directive's provisions for radon must be transposed to national legislation by November 2015. As part of an on-going review of the implications of the Directive for Scotland, the Drinking Water Quality Regulator (DWQR) need to collate the evidence on the presence of radon in drinking water and risk areas of likely high exposure to radon in drinking water from public and private drinking water supplies.

Method

The peer-reviewed and grey (from regulatory and other agencies) literature on radon occurrence in drinking water supplies in Scotland and the effects of radon on public health was assessed to identify conditions with the potential to increase exposure to radon in drinking water in Scotland. 'Areas of likely high exposure' to radon in drinking water due to underlying geology, as required in the Directive, were selected joining groundwater bodies with the radon potential map for Scotland, i.e. 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). The Radon potential map relates to the geological background identified by 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 1% and 10% refers to medium risk. This approach helped to explore scenarios of risk areas for radon drinking water to inform further policy action.

Policy Recommendations

- Representative baseline surveys are required to assess radon in drinking water in Scotland and should be targeted at the high-risk area to test whether this area is representative of 'areas of likely high exposure' to radon in drinking water due to underlying geology.
- Monitoring for assessing compliance with the radon parametric value should be targeted to public and private (type A) drinking water supplies served by groundwater.
- No monitoring is required in surface drinking water supplies.
- Action for Scottish Water: Baseline radon surveys are required in treatment plants and mitigation should be implemented before water enters the distribution network.
- Action for local authorities: Baseline radon surveys are required at point-of-use (tap) of type A-private groundwater supplies within the selected risk area to test whether the radon parametric value is exceeded; radon mitigation measures should be put in place at point-of-entry for effective radon reduction before water reaches the tap.
- The parametric value for radon in drinking water should aim at protection from exposure by the most hazardous pathway, i.e. inhalation, and be identified in the light of evidence from the radon baseline surveys to be carried out in 2015 in Scotland.
- A holistic approach to mitigating and protecting the population from exposure to radon from all sources should be adopted, e.g. water containing 1000 Bq/L of radon and a home with indoor-air radon at 200 Bq/m^3 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.

1.0 Introduction

1.1 Objective

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 will be 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.

1.2 Directive 2013/51/Euratom

The Directive's (1) requirements for tritium and total indicative dose (ID) are consistent with the provisions and scope of the Drinking Water Directive-DWD (2) (Table 1). Requirements for tritium and ID have already been transposed for public water supplies as the Water Supply (Water Quality) (Scotland) Regulations 2001, hereafter reported as the 'Regulations' (3) and for the private water supplies as the Private Water Supplies (Scotland) Regulations 2006, hereafter reported as the 'PWS Regulations' (4). 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 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 its decay products in drinking water. The new Directive, and especially its novel provisions for radon and the activities of its decay products, must be transposed to national legislation by November 2015.

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

Provisions and scope	Drinking Water Directive (2)		The Directive's recommendations (1)
	Regulations (3)	PWS Regulations (4)	
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	• 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.

1.3 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 naturally occurring radioactive materials (NORMs) such as uranium-bearing rock formations (Figure 1). Radon emits alpha and gamma radiation and has a half-life (i.e. the time required for one half of a given concentration of radon to decay) 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 (5-7). 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 (8-11).

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

(1) 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 causing cancer (12-14) due to radon gas itself (12).

(2) By inhalation of the radon gas that escapes tap water from freshly drawn radon-contaminated groundwater supplies. Only a small percentage of the total radon in indoor-air comes from tap water, the greatest source being the ground beneath the residence (5).

(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 (15-17).

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 (5, 16). 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 (16). In such cases, radon concentrations may be high enough to pose a threat to human health by ingestion and/or inhalation.

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 levels (18), it is not known whether or how many groundwater supplies are within these areas. In addition, until the publication of the new Directive, 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.

2.0 Method

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. The implications for Scotland of the Directive's provisions for radon in drinking water were assessed in three steps (see Table 2 for the supporting data):

Firstly, the 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 public was collected and assessed for its relevance with the Directive's provisions (section 3).

Secondly, recommendations for 'areas of likely high exposure' to radon in drinking water were developed, and, accordingly, a risk map for water supplies in Scotland was created (section 4). The steps followed to create the risk map using ArcGIS software are presented in Annex II.

Thirdly, the policy implications for a parametric value, action level and monitoring for radon in Scotland are discussed in the context of the key findings, the Directive's provisions and international

[1] 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 (19), are not examined.

Radon characteristics

- Gas
- Water soluble
- Inert gas
- Odourless
- Tasteless
- Naturally occurring
- Product of uranium decay
- Half-life=3.86 days
- Radon decay chain (progeny)=solid alpha and beta particles (e.g. polonium and lead; see also Figure 2)

Radon occurrence

- Ubiquitous
- Naturally occuring radioactive materials (NORMs), e.g. bedrock rich in uranium-238
- Groundwater
- Soils
- Outdoor air
- Drinking water form gorounwater sources
- Indoor-air via emanation from ground beneath home and degassing from tap water

Radon health effects

- By ingestion: stomach cancer
- By inhalation: lung cancer

Figure 1. Radon: characteristics, occurrence, and health effects to the general public. Source: World Health Organisation-WHO (5).

Table 2. Outline of the three-step approach and data analysed in each step to assess the implications for Scotland of the Directive's provisions for radon in drinking water.

Step	Source of data	Data description	Policy driver for collection of data
Step 1: Review	Scottish Environment Protection Agency (SEPA)	Data from monitoring public water supplies representative of sources (rivers, reservoirs, boreholes) and near radioactive waste discharge points [2]	Article 35 of the Euratom Treaty for the monitoring of the level of radioactivity in the air, water and soil (19)
	Scottish Water (SW)-DWQR	ID from public water supplies and private water supplies (PWS)	Drinking Water Directive (2) Regulations (3)
	Local authorities – DWQR	ID from type A-PWS	Drinking Water Directive (2) PWS Regulations (4)
	Policy – Health guidelines	•Health effects of radon in drinking water •Effective dose from radon in drinking water •Parametric values and action level in EU, UK, US	•WHO guidelines on exposure to radon (5, 16) •Commission's Recommendation 2001/928/Euratom (radon in water) (20) •Council Directive 96/29/Euratom (basic safety standards) (21) •National legislation from a variety of countries
	Peer reviewed literature	•Radon concentrations in drinking water in Scotland •Radon in water in relation to underlying geology and hydrology	•National legislation from a variety of countries •WHO guidelines on exposure to radon (5, 16) •Public health risk from exposure to radon
Step 2: Risk map	British Geological Survey (BGS) - Health Protection Agency (HPA)	Radon potential map for indoor-air	•Recommendations of the independent Advisory Group on Ionising Radiation-HPA (7)
	SEPA-BGS	Groundwater waterbody boundaries	Water Framework Directive (22)
	DWQR	Locations of public and private water supplies (type / source)	Drinking Water Directive (2); Regulations (3); PWS Regulations (4)
Step 3: Implications	Current report	•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)

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

3.1 What is the regulatory evidence on radon in drinking water in Scotland?

Gross alpha and gross beta radiation levels in representative public drinking water sources published in the RIFE reports since 1995 (23) are well below the screening levels recommended by WHO, i.e. 0.5 and 1 Bq/L, respectively (5) and laid down by the DWD, i.e. 0.1 and 1 Bq/L, respectively (2). In 2012, the mean annual radiation dose from consuming drinking water in the UK was mainly due to exposure to natural radionuclides and assessed as 0.027 mSv (23). On the basis of the data provided in the RIFE reports (23), 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 monitoring data from RIFE report (23) and regulatory correspondence (24) showed compliance with specified screening levels in all but two cases. There is no evidence that the small deviations from specified screening levels in these two cases could be related to radon contamination.

[2] Published annually in the Radioactivity in Food and the Environment (RIFE) reports since 1995 (23).

No monitoring has been considered necessary for radon and radon progeny or for ID and gross alpha and beta activities in type A-PWS served by groundwater or surface water in Scotland (25). A Food Standards Agency (FSA) publication in 2004 (cited in 25) reports that, based on evidence, there is no need to require local authorities to monitor type A PWS in Scotland for ID. In this respect, the PWS Regulations (4) report that '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'.

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 type A-PWS, lack of knowledge due to lack of measurements of radon, or gross alpha and beta activities.

3.2 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 mSv (6, 26, 27). 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 1 L 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 (28) (Table 3). In this context, ID from radon-contaminated drinking water may significantly contribute to total radiation dose and must thus be calculated.

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. Annual drinking water intake has been estimated for reference individuals. The estimates are 500 L/y for adults, 350 Ll/y for children and 150 L/y for infants (33). However, WHO recommends an average daily intake equal to 2 Ll per day (34) .

The ID from ingestion of radon ($ID_{ingestion}$) can be calculated using the following equation (10: Annex B):

$ID_{ingestion} = Conversion_{ingestion} \times Consumption_{tap\ water} \times$ Radontap 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 (10, 12) or 1.0 X 10^{-8} (10);
$Consumption_{tap\ water}$: average annual consumption of water;
$Radon_{tap\ water}$: annual average radon concentration in drinking water.

The ID from the radon emanating from tap water and then inhaled ($ID_{inhalation}$) can be calculated using a conversion factor and the equation recommended by UNSCEAR (10: Annex B) as follows:

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

where,

$Conversion_{inhalation}$: conversion factor of committed effective dose from inhalation of waterborne radon equal to 9 X 10^{-9} Sv/Bq (10: Annex B);
$Radon_{tap\ water}$: annual average radon concentration in drinking water;
$Transfer_{water\ to\ air}$: Radon transfer coefficient from tap water to air, equal to 0.1 l/m³ (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 by an individual indoors equal to 7,000 h.

The ID from inhalation of indoor radon from both ground-beneath-residence and waterborne sources ($ID_{indoor\ radon}$), can be calculated using the following equation (10: 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 $Radon_{tap\ water}$ 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 4). For more detail on the radon regulations in other countries see section 5.1

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)	References
Dose required to sterilise medical products	25,000	29
Typical total radiotherapy dose to cancer tumour	60	29
50% survival probability, whole body dose	4	29
Employee's dose limit (whole body)	0.02	30
Average annual dose from all sources in Cornwall	0.008	29
Average annual dose from total natural radiation (general population)	0.0026	29
Average annual dose from radon (general population)	0.0013	6, 26, 29
Range of ID from exposure to radon in drinking water in UK	10^{-5} - 10^{-3}	28, 31
Maximum ID from exposure to radon in drinking water in Finland	0.00324	32

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 #
$ID_{ingestion}$ (mSv/yr)	0.02	0.18	0.3	0.4	0.7	1.4	1.8
$ID_{inhalation}$ (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
$ID_{indoor\ radon}$ (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

Table 4 shows that:

- The total ID due to inhalation and ingestion of radon released from tap water (i.e. total ID from waterborne radon is almost twice as high as the IDingestion).
- 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/m^3, the latter being the action level established in Recommendation 90/143/Euratom (19) and Europe (35) and endorsed by the Health Protection Scotland (18).

3.3 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 X 10^{-4} (36-38), i.e. for every 1 Bq/L of radon in tap water an increase by 0.1 Bq/m^3 of radon in indoor-air is expected. This, however, depends on indoor conditions and domestic uses of water that have the potential to significantly increase radon degassing out of the water such as high indoor temperature, poor home ventilation, and heating or agitation of water through cooking, showering, and laundering (6).

3.4 What is the research evidence on 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 (39, 40). The major drivers for these studies have been: (i) the increasing awareness of radon as a geogenic hazard based on studies in the USA, e.g. (36); (ii) the development of radon-in-air portable detectors; and (iii) advances in scintillation counting technology, which enabled the analyses.

More specifically, Allen et al. (39) present radon concentrations found in the tap water of 800 schools in the UK, several of them in areas of Scotland associated with naturally occurring radioactive materials (NORMs) (Table 5). Similarly, Al-Doorie et al. (40) 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 school survey does not identify sources of water supply, i.e. surface or groundwater, number of schools, or ID (39). The well-survey in Aberdeen (40) does not specify whether the water storage conditions before the water reaches the tap are representative of the conditions across Scotland. Finally, both surveys give little or no evidence on the underlying geology. Therefore, although this evidence is reliable, it is not sufficient for assessing areas of likely high exposure to radon in drinking water in Scotland.

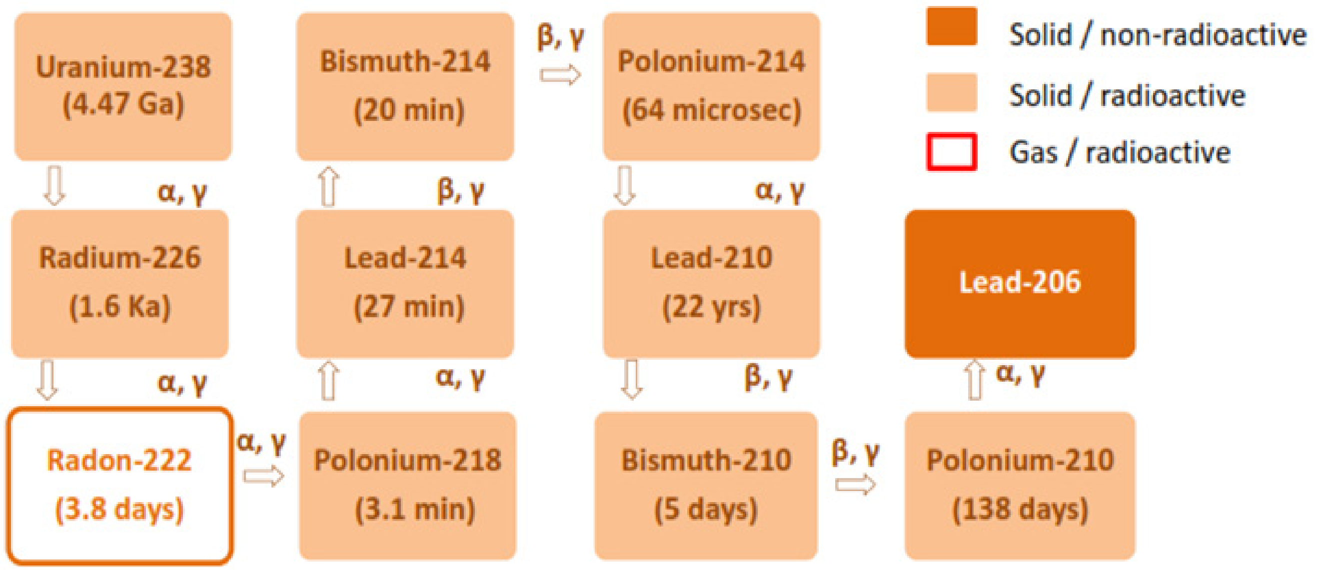
Table 5. Radon concentrations in tap water in selected areas in Scotland.

Area	Type of sample	Radon concentrations (min - max)	References
Dumfries and Galloway	Tap water (School)	0.7 – 71.1	39
Grampian	Tap water (School)	0.6 – 62.2	39
Highland	Tap water (School)	0.7 – 1.6	39
Orkney	Tap water (School)	0.7	39
Area of Aberdeen (igneous rock)	Tap water (private well)	40 – 76	40
Area of Aberdeen (meta-sedimentary rock)	Tap water (private well)	3 – 35	40

3.5 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 (radium-226), 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 (32, 41-43), 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 (43-46). 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 (43). There is no evidence on the influence of meteorological factors (rainfall, snow, surface pressure, temperature) on these processes.

Due to degassing, radon attains much lower concentrations in surface waters than in groundwater, where it can exceed 80,000 Bq/L (47). 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 (5). 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 (6, 48). This, however, is also controlled by building characteristics and the degree of ventilation (6). Radon concentrations in outdoor air in the UK are generally low, on average 4 Bq/m^3. Radon in indoor-air in UK dwellings is on average 20 Bq/m^3.



Decay rate (half-life) given in parentheses.
Type of radiation released in every decay: α= alpha radiation, β=beta radiation, γ=gamma radiation.

Figure 2. Uranium decay chain and radon progeny. Ga=billion years. Ka=thousand years. Source: (15).

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

Underlying Geology	Radon in water (Bq/L)	Reference
Seawater	<2	49
Surface freshwater	<4	49, 50
Springs	50 – 740	51, 52
Wells dug in soil	normal: 10-300	49
	granite 40-400	53
Wells in sedimentary rock	normal: 10-50 (rarely 150)	40, 49, 54
	metamorphic terrain: 37-370	55
Wells in crystalline rock	U-poor: 50-500	56
	U-rich granites 300-4,000 (max=63,000)	56, 57
	U rich permatites: max=30,000	49
U-ores	2,000-100,000	42, 49
Wells in granite bedrock	10^{-4}2,000	32, 53, 54, 58, 59
Boreholes in granite bedrock	Max=80,000	32, 47
Public water supplies in granite-rich areas	Max=1630	32

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/m^3 (18, 50).

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 groundwater bodies 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 (60). 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 (6).

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

1. Areas with uranium-bearing bedrock and associated soils.
2. Groundwater rather than in surface waters.
3. Areas with impermeable soils and confined aquifers.
4. Lowland areas.
5. 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	References
Restricting permeability – aeration –dilution with rainwater - recharge	Aquifer type	Confined > unconfined (impermeable > permeable)	6, 36, 54, 61-65
	Type of soil	Clay > gravel (impermeable > permeable)	
	Porosity	Low porosity > High porosity	
	Flow distribution	Low flow > High flow	
	Well use	Irregular > Regular	
	Land use	No effect	
	Bedrock type	Varies. Erodible rock (e.g. karst) > Non erodible	
Increasing downward (hydraulic) transport	Well altitude	Low altitude > High altitude	49, 54, 55, 66
	Well depth	Varies (aquifer and soil type)	
Increasing surface area of the source uranium-rich rock with water	Drilling frequency	High frequency > Low frequency	6, 54, 64
	Fractures-imperfections	More > fewer imperfections	
	Distance from fracture zone	Varies	

4.0 Risk Map for radon in groundwater in Scotland

4.1 Where are the radon-affected areas in Scotland?

The available evidence suggests that radon concentrations in drinking water in Scotland are much lower than in other parts of the world with similar underlying geology (39, 40). However, this evidence comes from only a few sites. There is a need to predict (model) radon occurrence by identifying the relationship between radon in groundwater and 'what earth delivers' in terms of radon. The latter quantity, or spatial variable, gives the geogenic radon potential (48). The 'Indicative Atlas of Radon in Scotland' (hereafter reported as the Atlas) jointly produced by BGS-HPA (67, 68) is based on this approach. Radon potential is the probability that a home that has not had a radon measurement in indoor-air will have a long-term average indoor-air radon concentration at or above the radon action level, which in the UK is 200 Bq/m^3.

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 (68). 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 geology (58, 59). The radon-affected areas with more than 10% of homes at or above action level for indoor-air radon include: the Siluro-Devonian uranium-rich granites of Aberdeenshire (Grampian) and Helmsdale area (Highlands); and the Middle Old Red Sandstone in the Orkney Islands and Caithness (Highlands) (Figure 3).

In addition, areas with higher than average radon levels in indoor-air are associated with the (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.

Radon potential: % of homes 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

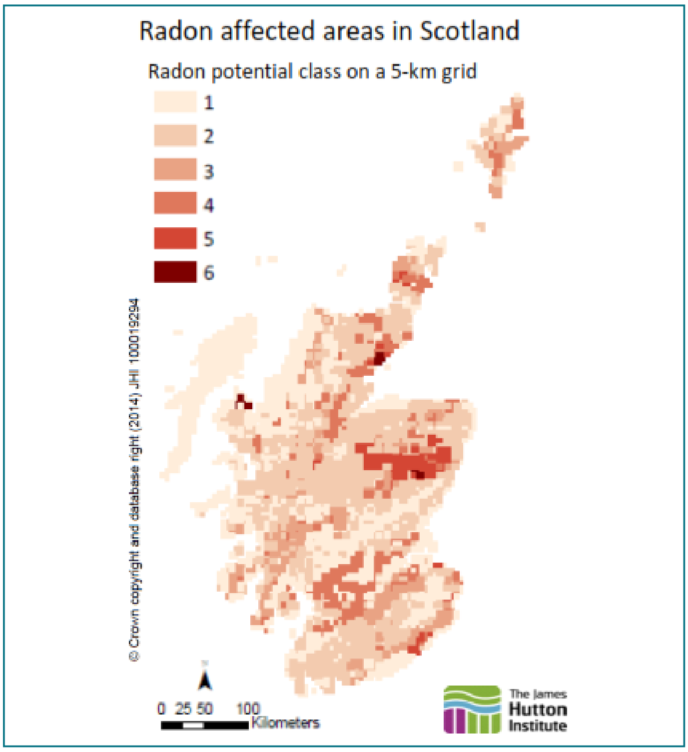


Figure 3. Radon potential classification in Scotland. The radon potential ArcGIS shapefile, provided by BGS (Annex I), had been intersected with the British National Grid 5 km tile boundaries; classification is based on selecting the highest radon potential class (1-6) that occurred within each 5-km square. Data source: BGS-HPA.

4.2 Caveats of using the Atlas to identify risk areas for radon in groundwater

There are a number of caveats which concern the use of the Atlas for identifying risk areas for radon in groundwater, as follows:

- 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, most of these cases refer to unconfined aquifers where radon concentrations are expected to be lower. Therefore, it is believed that uncertainties in radon distribution are counteracted by the lower risk of elevated values.

- Uranium mineral precipitation in bedrock with low uranium content may increase radon in groundwater thus causing a mismatch between underlying geology, radon potential, and radon in groundwater.

- 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/m^3 but maximum values exceed 6000 Bq/m^3 (69). This spread of indoor-air values can partly be explained by varying conditions in ventilation and insulation and may lead to a mismatch between radon in indoor-air and radon in tap-water.

- 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.

- The output is based on, and limited to, an interpretation of the records in the possession of BGS and HPA at the time the baseline radon indoor-air measurements were taken, i.e. 2008 for Scotland (70). 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 to predict areas of likely high exposure to radon in drinking water in Scotland and target baseline surveys to obtain more information.

4.3 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 and assessed in this report (see section 3):

(1) Risk of elevated radon concentrations in the tap water coming from surface public or private drinking water supplies is minimal.

(2) 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 1% radon potential, then all water supplies sharing the same groundwater waterbody will be at risk of medium or high 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 Annex 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
≥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. However, the alternative scenarios add uncertainties rather than information on likely high exposure to radon. This is because of the coarse resolution of the Atlas and the relatively low number of homes at risk of being at or above action level for radon in indoor-air in Scenarios 1, 2, and 3.

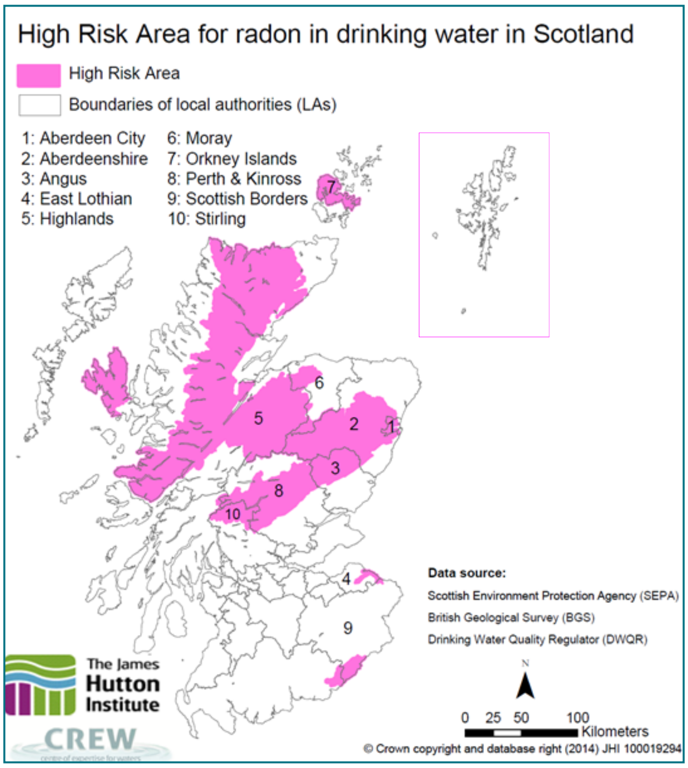


Figure 4. High-risk area for radon in drinking water in Scotland. The map shows high-risk areas within each local authority.

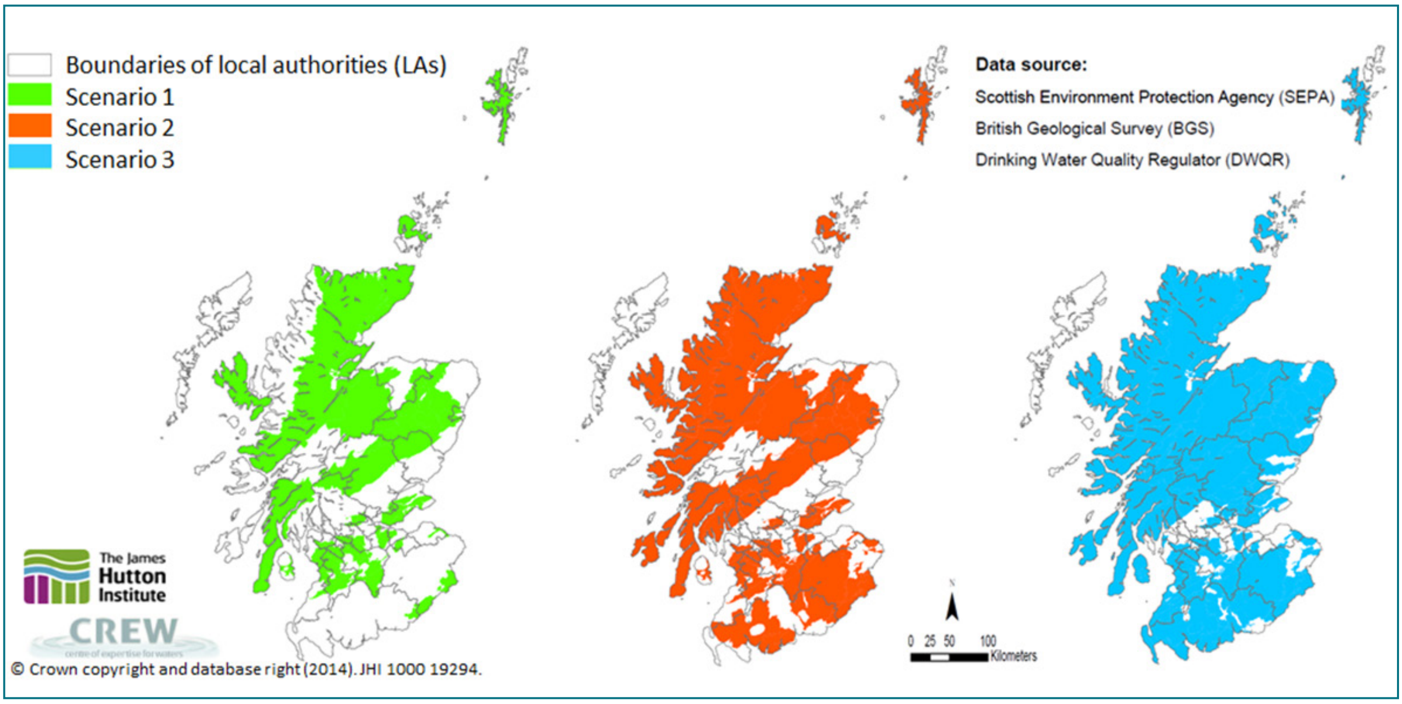


Figure 5. Alternative risk area scenarios for risk of exposure to radon in groundwater. The maps show risk areas within each local authority (LA) in each scenario. See also Table 8.

4.4 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 type A-PWS. The high-risk area includes 31% of all public groundwater supplies (Figures 6) and 33% of all type A-PWS boreholes, 30% of all type A-PWS springs and 24% of all type A-PWS wells (Figure 7). The type A-PWS served by surface water take water from rivers, streams, lochs and rainwater and thus are not considered to be at risk from geogenic radon within or outwith the high-risk area. In addition, 10 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 type A-PWS springs (Table 10).

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

Table 9. Comparative presentation of numbers of groundwater public and type A-PWS in the high-risk area and each of the three alternative risk area scenarios. Data source: DWQR.

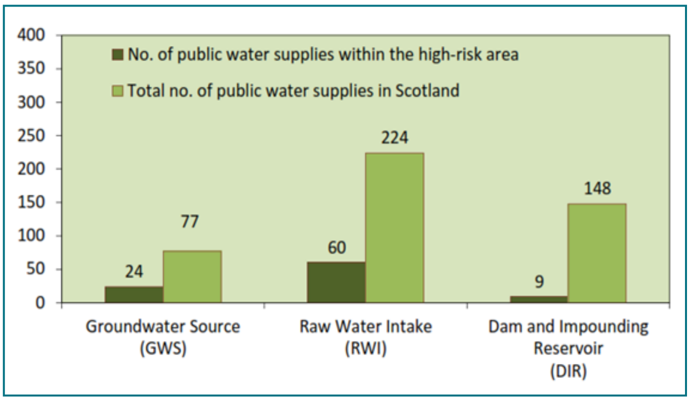
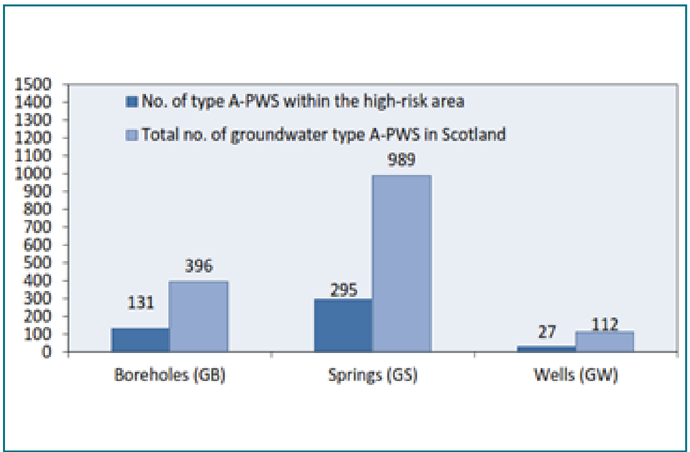


Figure 6. Number of public groundwater and surface water drinking water supplies in the high-risk area compared with the total number of public drinking water supplies in Scotland.



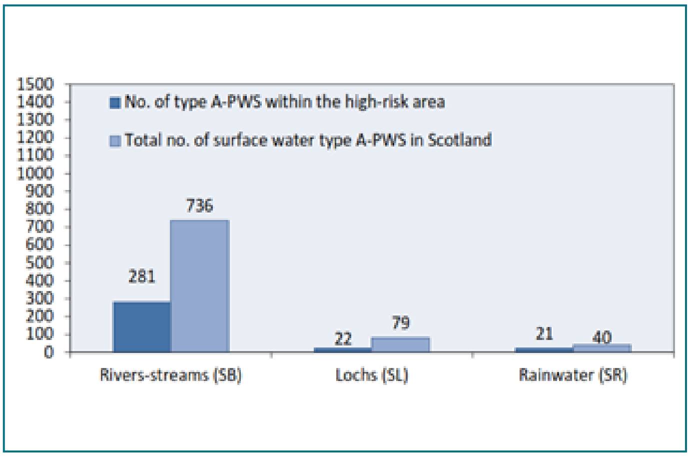


Figure 7. Number of groundwater (left) and surface water (right) private water supplies (type A-PWS) in the high-risk area compared with the total number of type A-PWS per source type in Scotland.

Table 10. Number of groundwater type A-PWS in the high-risk area and in each of the three alternative risk area scenarios (Scenarios 1, 2, and 3).

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

5. What can policy-makers do about this?

5.1 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 of 50-500 Bq/L for public water supplies and 120-1000 Bq/L for small (such as the type A-PWS in Scotland) water supplies (62). A common characteristic justifying the specified parametric values 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 private 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 (71).

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 simultaneously address radon that enters indoor-air from soil under homes and building (72). This value corresponds to background levels in outdoor air (i.e. about 14 Bq/m^3). States that have not adopted the MMM 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 with the aim to 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 in US and UK 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-air (73).

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.

5.2 Selecting the risk area for radon in groundwater

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 has been collected in this report. As a result, a high-risk area and alternative risk area scenarios have been proposed to inform policy action and help SW and Scottish local authorities to 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 planned for 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 to target the baseline representative surveys to a risk area.

Table 11 provides a checklist of strengths and limitations of the high-risk area and the alternative risk area scenarios in terms of feasibility of baseline representative surveys and regulatory monitoring to help DWQR formulate future action. In the case of selecting the high-risk area for carrying out these surveys, two options could be considered.

Option 1 involves comparing radon levels between the high-risk area and the areas in scenarios 1, 2, and 3 by means of random sampling within each area to inform decisions on the range of values and where monitoring or mitigation is required; practically this means sampling almost all type A-PWS in Scotland (see Tables 9 and 10). 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, and offers the opportunity for comparing radon range within the high-risk area against radon range outwith the high-risk area, i.e. in areas referring to scenarios 1, 2, and 3. 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. SW: Scottish Water. LA: Local Authority

Options for design of baseline surveys	Strengths	Limitations
Option 1: comparison between radon data from high-risk area and areas in scenarios 1, 2, and 3	•Representativeness, in line with the Directive's requirement, as both areas of high and medium radon potential will be surveyed •Proximity/feasibility, as PWS could be selected on the basis of enabling lab analyses within appropriate timescales from sampling •Usefulness as it provides baseline radon evidence in the surveyed combinations of radon potential squares and groundwater bodies	The design has to be carefully planned to ensure that: •the surveyed type A-PWS are randomly selected and representative of hydrogeological conditions •the design is not biased towards areas of low exposure because areas in scenarios 1, 2, and 3 include more type A-PWS than the high-risk area •no extra resources are used without adding information on where to monitor for capturing high radon values in drinking water
Option 2: radon data from high-risk area only	•Feasible within the specified timescales for the transposition of the Directive into Scots law by November 2015, as it has the lowest number and spatial spread of type A-PWS	•Without comparisons against a data from areas outwith the high-risk area it remains uncertain whether the baseline surveys are representative of conditions in Scotland

5.3 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 value and action level for radon in drinking water may be exceeded, and under what conditions. Therefore, we recommend that:

- No baseline monitoring is required in surface water supplies.

- 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 public groundwater supplies are optional when residence time of water in treatment plants is long enough to allow radon decay to levels below the parametric value; however, as this depends on radon concentrations at the source it is wise to sample all public groundwater supplies within the selected risk area.

- Baseline surveys in type A-PWS are required for supplies taking water from groundwater sources (wells, boreholes or springs). Sampling in this case should be carried out at the point of compliance, i.e. the tap water. The baseline surveys will help LAs to target monitoring to comply with the Directive's provisions, and plan the awareness campaign for mitigation and remedial action, if required.

- Seasonal baseline surveys or compliance monitoring are not required, as there is no evidence of meteorological controls on geogenic radon in the rock formations dominating Scotland.

- Replicate tap water samples from the same distribution network of groundwater type A-PWS are required, together with recording of number of properties and type and source of supply, to assess any causes of variation in radon levels from year-to-year and practical radon mitigation methods before the water reaches the tap.

- Aligning radon baseline surveys to inform the transposition of the Directive with the monitoring visits in compliance with the PWS Regulations (4) 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 radon (18). 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, additional options for local authorities within the high-risk area or the risk area of scenario 1, depending on selected risk area, include:

- Target baseline surveys and 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 and have been found to be at or above the action level for indoor-air radon (i.e. 200 Bq/ m³).

- Target surveys in all homes served by groundwater Type A-PWS and free testing in groundwater type B-PWS.

- Target awareness campaign for radon mitigation measures in drinking water.

5.4 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 (10, 12). Such increases of radon in indoor-air correspond to a rise in lung cancer risk by 10 to 16% (70, 74-77). It must be emphasised 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-ICRP (78); 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 (US EPA), 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 US EPA in developing national drinking water standards (79).

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 (see section 3.2; Table 4), 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.

5.5 What are the options for a parametric value?

The available options for parametric value are:

- Setting a value within the range in the new Directive's recommendations, i.e. between 100 Bq/ and the action level value (1000 Bq/L).
- Setting a value at the lower end of the recommended range.
- Setting 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 regulations and endorsed by the European Commission (80). 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 at 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 users and 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, i.e. aeration, which 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 ways (81):

1. 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.

2. 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 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. A holistic approach 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 context, it is reasonable to assume that a single standard value for a parametric value and action level would help communicate a clear message to the public about the need for mitigation at levels below or at the specified single standard value and for remedial action, in the case of exceedances.

The parametric value will be decided on the basis radon measurements within the selected risk area in a follow-up project.

6.0. Concluding remarks

This report collates existing evidence to inform DWQR about the implications for Scotland of the provisions and scope of the Directive. It also offers information and criteria to help select the most practical option to implement the Directive's recommendations on a parametric value and action level for radon in drinking water. It also analyses the sources and health implications of radon in drinking water and proposes radon-affected areas from a groundwater perspective in Scotland.

The key findings can be summarised as follows:

1. Radon (222Rn) 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 (i.e. the time required for one half of a given concentration of radon to decay) of 3.8 days. The radioactive products of its decay chain (radon progeny) are all solid and also give off radiation, either alpha and gamma radiation (i.e. polonium) or beta and gamma radiation (i.e. lead and bismuth).

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

- By ingestion of radon-contaminated groundwater before radon degassing to indoor-air.
- 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 but the health risk due to inhalation of radon emanating from tap water is almost twice as high as the health risk due to ingestion of radon-contaminated drinking water.
- By inhalation of the radon progeny that may cling on dust particles found in the indoor-air.

3. There is limited evidence on radon levels in 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.

4. Radon occurrence in drinking water is controlled by underlying geology, hydrological processes influencing groundwater, water supply type, indoor conditions, and domestic uses of water.

- Higher radon concentrations are expected in areas underlain by uranium-bearing bedrock and associated soils. In Scotland, such areas are found in Aberdeenshire, Helmsdale, the Orkney Islands, the Southern Uplands, the Argyll area, and in limestone throughout the country.
- High radon concentrations are associated with groundwater rather than surface waters, and especially with groundwater bodies that are subject to frequent drilling and restricted radon degassing, water transport or dilution with rainfall.
- There is higher risk of exposure to radon in drinking water from small private or public supplies than from large public water supplies. Public water supplies come to households via large storage systems with long residence times that allow radon to escape into the air or decay to very low levels before reaching the consumer. By contrast, the time between pumping and consumption of water from small private water supplies or small public networks, is well within radon's half-time.
- High indoor-air temperature and heating or agitation of water before use increase radon degassing out of water.

5. The high-risk area for radon in drinking water refers to the area presenting the highest risk of exposure to radon in drinking water and includes 24 out of 77 public supplies and

453 out of 1497 type A-private groundwater drinking water supplies in 10 out of 32 local authorities.

6. Three alternative scenarios for risk areas for radon in groundwater can be identified to include areas with medium and low risk of exposure to radon in drinking water. However, these alternative scenarios add uncertainties rather than information on likely high exposure to radon.

The report also provided recommendations on carrying out baseline surveys and monitoring for radon in drinking water, as follows:

- Representative baseline surveys are required to assess radon in drinking water in Scotland and should be targeted at the high-risk area to test whether this area is representative of 'areas of likely high exposure' to radon in drinking water due to underlying geology.
- Monitoring for assessing compliance with the radon parametric value should be targeted to public and private (type A) drinking water supplies served by groundwater.
- No monitoring is required in surface drinking water supplies.
- Action for Scottish Water: Baseline radon surveys are required in treatment plants and mitigation should be implemented before water enters the distribution network.
- Action for local authorities: Baseline radon surveys are required at point-of-use (tap) of type A-private groundwater supplies within the selected risk area to test whether the radon parametric value is exceeded; radon mitigation measures should be put in place at point-of-entry for effective radon reduction before water reaches the tap.
- The parametric value for radon in drinking water should aim at protection from exposure by the most hazardous pathway, i.e. inhalation, and be identified in the light of evidence from the radon baseline surveys to be carried out in 2015 in Scotland.
- A holistic approach to mitigating and protecting the population from exposure to radon from all sources should be adopted, e.g. water containing 1000 Bq/L of radon and a home with indoor-air radon at 200 Bq/m^3 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.

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

(Based on references: 1, 5, 12, 27, 78, 79)
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: 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):

1. 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;

2. 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;

3. Each 5-km grid square is coloured according to the highest radon potential found within it.

Annex I-References

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Annex II: Steps followed to identify risk area scenarios for radon in groundwater

The data sources used for identifying the risk area include:

- The locations (site reference) and source of water of public and type A-private water supplies in Scotland, provided by the DWQR.

- 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 Council Directive 2000/60/EC – the Water Framework Directive (Figure_Annex II).

- The 5-km grid square of the Indicative Atlas of Radon in Scotland (Miles et al. 2011) described in Annex 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_Annex II) to create the 'supplies-hydro' layer.

2. Joining the 'supplies-hydro' layer with radon potential map ('geology' layer, Figure_Annex II) 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 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

4. (For each risk area) The selected features at Step 3 are used to intersect the 'hydro' layer to produce the 'groundwater' layer for the high-risk area and each of the alternative risk area scenarios.

5. Steps 1 to 4 are done separately for public and private water supplies. Then, the 'groundwater' layers of public and the private supplies are joined to form the combined layer for each risk area.

The final output to DWQR, which accompanies the current report, includes a polygon shapefile for the high-risk area and each of the alternative risk area scenarios, a point shapefile of groundwater public supplies for each risk area, and a point shapefile of groundwater type A-PWS for each risk area.

Annex II-References

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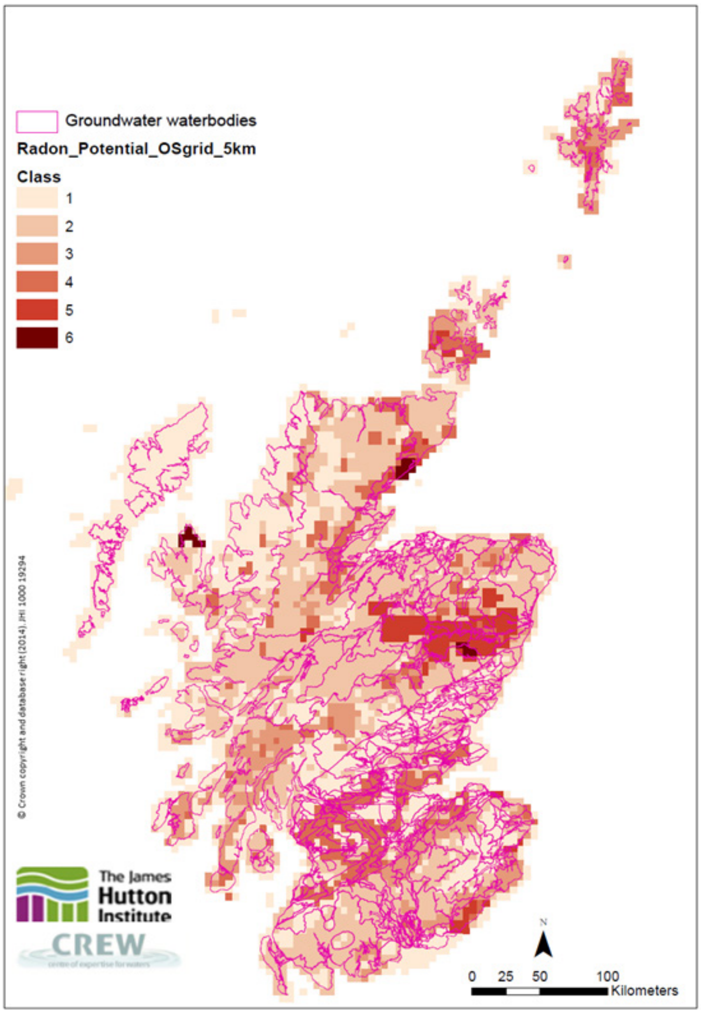

Figure_Annex II. Groundwater bodies ('hydro' layer) overlain on the radon potential grid square ('geology' layer). Data source: SEPA, BGS

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