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Shallow circulation groundwater – the main type of water containing hazardous radon concentration

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Abstract. The main factors affecting the value of ^{222}Rn activity concentration in groundwater are the emanation coefficient of reservoir rocks (K_{em}), the content of parent ^{226}Ra in these rocks (q), changes in the volume and flow velocity as well as the mixing of various groundwater components in the circulation system. The highest values of ^{222}Rn activity concentration are recorded in groundwaters flowing towards an intake through strongly cracked reservoir rocks undergoing weathering processes. Because of these facts, waters with hazardous radon concentration levels, i.e. containing more than 100 Bq dm^{-3} ^{222}Rn, could be characterised in the way that follows. They are classified as radon waters, high-radon waters and extreme-radon waters. They belong to shallow circulation systems (at less than a few dozen metres below ground level) and are contemporary infiltration waters, i.e. their underground flow time ranges from several fortnights to a few decades. Because of this, these are usually poorly mineralised waters (often below 0.2–0.5 g dm^{-3}). Their resources are renewable, but also vulnerable to contamination.

Waters of this type are usually drawn from private intakes, supplying water to one or at most a few households. Due to an increased risk of developing lung tumours, radon should be removed from such waters when still in the intake. To achieve this aim, appropriate legislation should be introduced in many countries.

1 Introduction

Radon is a radioactive noble gas, highly soluble in water. Because of the half-life of its natural isotopes, it is practically only ^{222}Rn that plays an important part in the groundwater and surface-water environment. The half-life of this radionuclide is 3.8224 days (Collé, 1995a, b). Thanks to this, ^{222}Rn isotope migrates with groundwaters at the distance enabling it to reach intakes and then – households. The value range of concentration activity of water-dissolved ^{222}Rn is very wide. The concentration of this gas in surface waters decreases very fast, as it is released into the atmosphere. Its concentration in the waters of streams and rivers oscillates from a fraction of a becquerel to a few dozen becquerels in a litre. In groundwaters, on the other hand, ^{222}Rn activity concentrations vary from a fraction of a becquerel to hundreds of thousand becquerels in a litre, i.e. within six orders of magnitude. This fact has become a basis for groundwater classification based on ^{222}Rn activity concentration (Table 1).

If radon waters, particularly high-radon or extreme-radon waters, are present in an intake supplying households, the residents are exposed to an extra effective dose from ionising radiation in the building. However it is not connected with consuming radon-containing water, but inhaling radon released from water, especially in bathrooms and kitchens while boiling (heating) water, particularly when it is sprayed – in a bath or a shower, or when doing the laundry or washing up (e.g. Bodansky et al., 1987; Cothern and Smith, 1987; Commission Recommendation, 2001; Kim et al., 2001; WHO, 2004; Swedjemark, 2004; López et al., 2004). The inhaled radon and particularly its short-lived daughters increase the risk of developing lung cancer (e.g. Bodansky et al., 1987; Cothern and Smith, 1987; WHO, 2004; Swedjemark, 2004; Krewski et al., 2005).

Aware of the risk connected with using radon-rich waters in households, some countries (e.g. USA, UK, Finland, Sweden, Norway, Russia, the Czech Republic or the Slovak Republic) have introduced limits of allowable ^{222}Rn activity concentration in consumable waters (reference levels), i.e. those which are supplied to households (Åkerblom, 1999). Appropriate guidelines in this area have also been adopted by international organisations (WHO,

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Table 1. Groundwater classification based on ^{222}Rn content (according to Przylibski, 2005).

Groundwater name	^{222}Rn activity concentration in groundwater $[\mathrm{Bq\,dm^{-3}}] = [\mathrm{kBq\,m^{-3}}]$
Radon−free water	< 1
Radon−poor water	1–9.9(9)
Low−radon water	10–99.9(9)
Radon water	100–999.9(9)
High−radon water	1000–9999.9(9)
Extreme−radon water	≥10 000

2004; Commission Recommendation, 2001). Any recommendations or legal regulations require monitoring ^{222}Rn activity concentration, and in the case of recording high values, they recommend or require removing radon from water while it is still in the intake, or they prohibit using it in households. The most reasonable limit requiring the monitoring of radon concentration in groundwater still present in an intake seems its activity concentration of $100\,\mathrm{Bq\,dm^{-3}}$. If this level is significantly (several times) and repeatedly higher, then action should be taken to remove radon from water. It is best to keep ^{222}Rn activity concentration in intake water below the value of $100\,\mathrm{Bq\,dm^{-3}}$ (WHO, 2004). Removing radon is absolutely necessary when ^{222}Rn activity concentration exceeds $1000\,\mathrm{Bq\,dm^{-3}}$ (WHO, 2004; Commission Recommendation, 2001). The regulations introduced in Sweden do not allow using waters with ^{222}Rn activity concentration of over $1000\,\mathrm{Bq\,dm^{-3}}$ at all (Åkerblom, 1999).

Studies, also those conducted by the author (Przylibski, 2000a, b, c, 2005, 2007; Przylibski and Żebrowski, 1996, 1999; Przylibski et al., 2001, 2002, 2004; Przylibski and Adamczyk-Lorenc, 2007) on the occurrence of radon, particularly ^{222}Rn isotope, in groundwater environment, have enabled obtaining a lot of information on the hydrogeochemistry of this radioactive gas (e.g. Rama and Moore, 1984; Fleischer, 1983, 1987; Greeman and Rose, 1996; Sun and Semkow, 1998; Luo et al., 2000; Wood et al., 2004; Barillon et al., 2005; Sasaki et al., 2004, 2005; Choubey et al., 2007). The knowledge of the origin, pattern and scale of radon migration in the groundwater environment enables us to define the type of waters involving a risk of the presence of high radon concentrations. Such waters should not be used in households or they should be de-radoned shortly before piping them to buildings.

The author's opinion is that it is now already possible to specify quite precisely and to characterise the type of groundwater which usually contains the highest and the most hazardous concentration of ^{222}Rn.

2 Facts, their interpretation and discussion

In order to specify a particular type of groundwater which can be expected to contain the highest values of ^{222}Rn activity concentration, it is essential to characterise factors determining the amount of radon which could be dissolved in groundwater and the distance over which it is transported with this groundwater. According to the results of the author's own research (Przylibski, 2000a, c, 2005), the following factors should be considered as having the biggest influence on the concentration of ^{222}Rn activity in groundwaters:

- emanation coefficient of reservoir rocks (K_{em}),
- content of parent ^{226}Ra in these rocks (q),
- changes in the volume and flow velocity as well as mixing of various groundwater components in a circulation system.

^{222}Rn activity concentration in groundwaters rises with the rise in the emanation coefficient of reservoir rocks and the rise in ^{226}Ra content in these rocks. Studies conducted by the author (Przylibski, 2005) in the area of the Sudetes (SW Poland) (Fig. 1) have demonstrated that distinctly increased values of ^{222}Rn activity concentration in groundwaters may be expected only when reservoir rocks exhibit increased values of both emanation coefficient and ^{226}Ra activity concentration. It has to be stressed here that clearly higher values of ^{222}Rn activity concentration were recorded only when the values of both q and K_{em} were higher at the same time than $30\,\mathrm{Bq\,kg^{-1}}$ and 0.1 respectively (Fig. 2). Changes in flow velocity and the volume of water in a circulation system, as well as the process of mixing various groundwater components, may lead to mutually exclusive results, i.e. increasing or decreasing of ^{222}Rn activity concentration (Przylibski, 2005).

In order to calculate the K_{em} of reservoir rocks, the author used an equation (Przylibski, 2000c), later slightly modified and supplemented (Przylibski, 2005), which links the activity concentration of ^{222}Rn dissolved in groundwater ($c_{p\mathrm{Rn}}$) with the emanation coefficient of its reservoir rocks (K_{em}), the activity concentration of parent ^{226}Ra in these rocks (q), the physical properties of reservoir rocks affecting its permeability to waters and gases (ρ_{s}, n), as well as the activity concentration of ^{226}Ra^{2+} ions dissolved in this groundwater ($c_{p\mathrm{Ra0}}$):

$$c_{p\mathrm{Rn}} = \frac{(1-n)\cdot\rho_s\cdot q\cdot K_{\mathrm{em}}}{n} + c_{p\mathrm{Ra0}} \quad (1)$$

where:
K_{em} – coefficient of ^{222}Rn emanation from reservoir rock to groundwater, [−],
n – effective porosity coefficient of reservoir rock, [−],
$c_{p\mathrm{Rn}}$ – ^{222}Rn activity concentration in groundwater, $[\mathrm{Bq\,m^{-3}}]$,

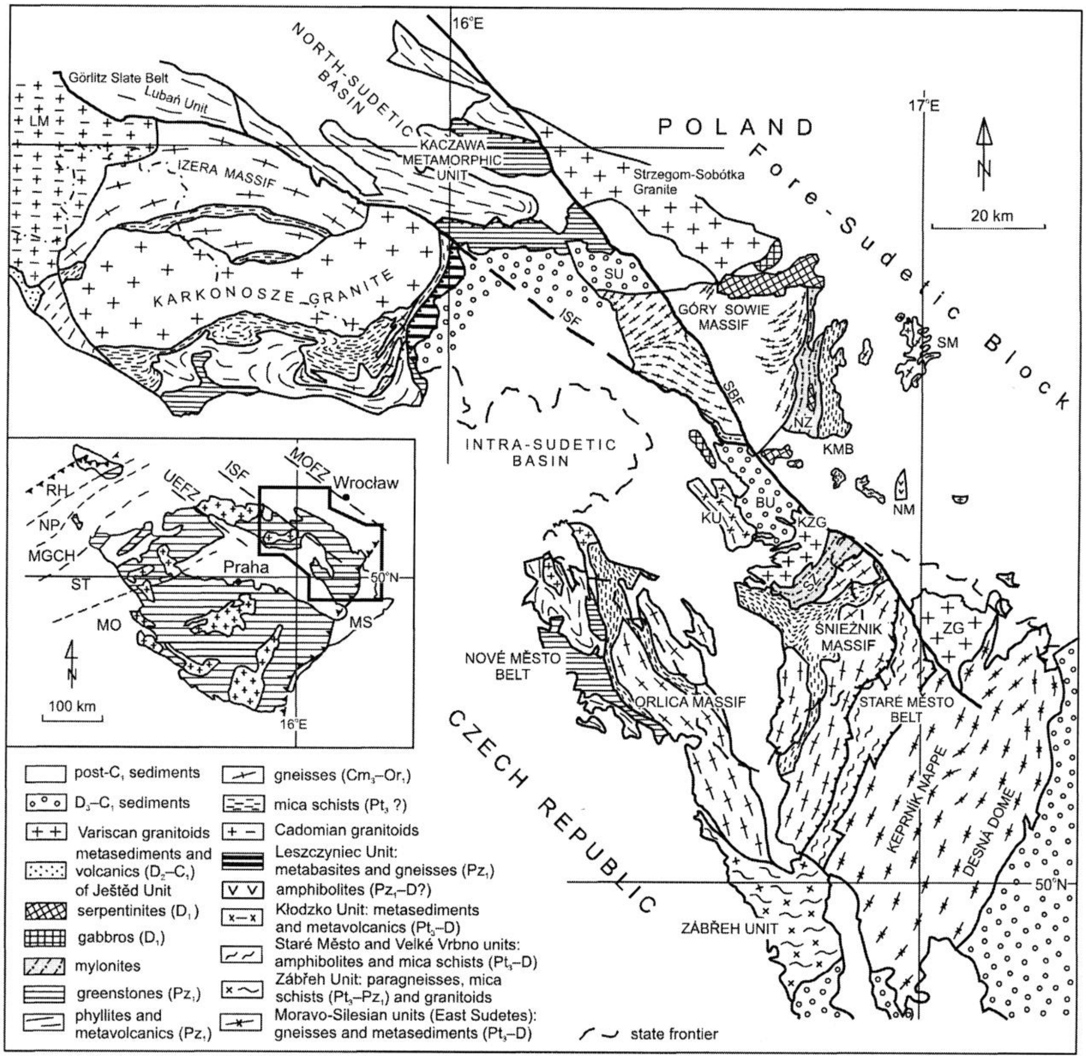

Fig. 1. Geological sketch map of the Sudetes (after Aleksandrowski et al., 1997). Explanations: BU – Bardo Sedimentary Unit, ISF – Intra-Sudetic Fault, KMB – Kamieniec Metamorphic Belt, KU – Kłodzko Metamorphic Unit, KZG – Kłodzko-Złoty Stok Granite, LM – Lusatian Massif, MGCH – Mid-German Crystalline High, MO – Moldanubian Zone, MOFZ – Middle Odra Fault Zone, MS – Moravo-Silesian Zone, NM – Niedźwiedź Massif, NP – Northern Phyllite Zone, NZ – Niemcza Shear Zone, RH – Rhenohercynian Zone, SU – Świebodzice Sedimentary Unit, SBF – Sudetic Boundary Fault, SM – Strzelin Massif, ST – Saxothuringian Zone, SZ – Skrzynka Shear Zone, UEFZ – Upper Elbe Fault Zone, ZG – Žulová Granite. Springs and intakes examined by the author were located within: Izera Massif, Karkonosze Granite, Intra-Sudetic Basin, Strzegom-Sobótka Granite, Kamieniec Metamorphic Belt, Śnieżnik Massif, Orlica Massif, Kaczawa Metamorphic Unit, Góry Sowie Massif.

$c_{p\mathrm{Ra0}}$ – ^{226}Ra activity concentration in groundwater, [Bq m^{-3}],
ρ_s – grain skeleton density, [kg m^{-3}],
q – ^{226}Ra content in reservoir rock, [Bq kg^{-1}].

This equation expresses radioactive equilibrium in a closed system. One should also remember that it is not only the absolute value of the activity concentration of parent ^{226}Ra in these rocks that affects the activity concentration of radon dissolved in groundwater filling their pores and fissures. A vital factor is the distribution of ^{226}Ra atoms in rock. The nuclei of this radium isotope release far more ^{222}Rn atoms into the pore space (and fissures) if they are found in outer zones of mineral crystals or are contained in minerals present in the immediate neighbourhood of the surface of cracks and fissures or pores (Rama and Moore, 1984; Fleischer, 1983, 1987; Greeman and Rose, 1996; Sun and Semkow, 1998; Luo et al., 2000; Wood et al., 2004).

The coefficient of ^{222}Rn emanation from reservoir rocks to groundwaters mostly ranges between 0.01 to 0.1, which means that from 1 to 10 % of ^{222}Rn atoms formed as a result of the decay of ^{226}Ra nuclei found in the structures of minerals building these rocks or present on the surfaces of

Table 2. Values of the parameters used for the K_{em} calculation and obtained from Eq. (1) K_{em} values for reservoir rocks supplying with groundwater selected intakes in the area of the Sudetes (according to Przylibski, 2005). Symbol explanations the same as for Eq. (1).

Intake	c_{pRn}	c_{pRa0}	q	ρ_s	n	K_{em}
	[$Bq\,m^{-3}$]		[$Bq\,kg^{-1}$]	[$kg\,m^{-3}$]	[−]	[−]
IZERA MASSIF CZERNIAWA-ZDRÓJ						
nr 4	35 100	780	38.8	2700	0.030	0.01
P-2	15 900	790	44.2	2650	0.035	0.005
IZERA MASSIF ŚWIERADÓW-ZDRÓJ						
Górne A	441 100	46	73.3	2500	0.060	0.15
1A	86 800	525	73.3	2650	0.035	0.015
MCS-3	892 400	68	55.5	2500	0.060	0.41
MCS-4	988 800	67	55.5	2500	0.060	0.455
MCS-5	1 517 000	44	55.5	2500	0.060	0.70
MCS-6	668 000	36	55.5	2500	0.060	0.31
INTRA-SUDETIC BASIN SZCZAWNO-ZDRÓJ						
Marta	215 700	706	29.5	2450	0.100	0.33
Młynarz	32 300	77	26.5	2450	0.100	0.055
INTRA-SUDETIC BASIN POLANICA-ZDRÓJ						
P-300	5100	1009	14.2	2450	0.150	0.02
Pieniawa Józefa II	22 000	120	14.2	2400	0.180	0.14
Wielka Pieniawa	16 800	270	14.2	2400	0.180	0.105
INTRA-SUDETIC BASIN GORZANÓW						
nr 5	34 600	38	20	2400	0.210	0.19
nr 6	4900	84	20	2400	0.210	0.03
nr 7M	17 000	40	20	2400	0.190	0.08
KARKONOSZE GRANITE CIEPLICE ŚLĄSKIE-ZDRÓJ						
nr 1 Marysieńka	11 000	19	63.8	2550	0.035	0.005
nr 2 Sobieski	140 300	24	63.8	2500	0.040	0.04
ŚNIEŻNIK MASSIF LĄDEK-ZDRÓJ						
Chrobry	137 100	10	47.3	2500	0.060	0.075
Jerzy	1 109 000	88	47.3	2450	0.065	0.665
L-2 (Zdzisław)	117 100	12	47.3	2600	0.030	0.03
Skłodowska-Curie	329 500	26	47.3	2500	0.060	0.18
Wojciech	218 600	15	47.3	2500	0.060	0.12

pores, cracks and fissures are dissolved in groundwaters (Table 2). In the zones of intensive weathering, affecting the rise in crack density and rock porosity, as well as zones disturbed by intensive brittle tectonic deformations, K_{em} values can reach 0.3 or even 0.7 (Table 2). Theoretical studies demonstrate that in specific conditions, the emanation coefficient can reach values of up to 0.75 (Sasaki et al., 2005).

The process of mixing various groundwater components may lead to changes in ^{222}Rn activity concentration in water flowing to an intake. Radon content usually increases with a rise in the proportion of a water component flowing through a zone of cracked, weathered and ^{226}Ra-rich reservoir rocks in the groundwater mixture flowing out of them. This is usually the infiltration component of shallow circulation (Przylibski, 2005).

The above facts should be also supplemented with the results of the author's research into the occurrence of parent $^{226}Ra^{2+}$ ions in groundwaters. Theoretically, they could be also an additional source of ^{222}Rn atoms dissolved in groundwaters. Measurements performed in over 100 intakes in SW Poland (the Sudetes) have clearly demonstrated that in the vast majority of groundwaters (85 % of studied intakes), at

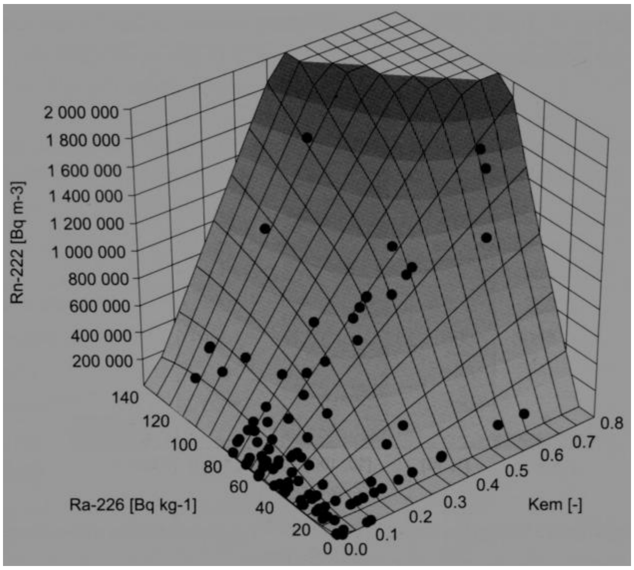

Fig. 2. Correlation between mean ^{222}Rn activity concentration in the groundwater and mean content of ^{226}Ra in its reservoir rock (q) and the value of the emanation coefficient (K_{em}) of this rock for 111 selected groundwater intakes in the area of the Sudetes (SW Poland) (according to Przylibski, 2005).

least 99 % of ^{222}Rn atoms originate in reservoir rocks, while hardly 1 % are formed as a result of radioactive transformation of $^{226}Ra^{2+}$ ions dissolved in these waters (Przylibski, 2005; Przylibski and Żebrowski, 1996, 1999; Przylibski et al., 2001, 2002) (Table 3).

The last important issue is the distance at which ^{222}Rn migrates with groundwaters. This distance depends chiefly on the flow velocity of water and is mainly determined by the kind of medium i.e. the type of reservoir rock. The lowest flow velocity is characteristic of a porous medium (permeable due to the effective porosity), higher – of a fissured one, and the highest – of large karst systems. Its changes range from fractions of a metre through dozens to hundreds of metres per 24 h (Bear, 1972, 1979; Zuber et al., 1995). The distance of radon transport from its place of formation as a result of nuclear transformation alpha of ^{226}Ra nucleus in mineral structure is also strictly limited by the lifetime of the ^{222}Rn isotope. If we agree that ^{222}Rn atoms can be transported for at most 38 days, i.e. for the time $10\,T_{1/2}$, while only 0.1 % remain from the initial number of nuclei, then the distance of radon transport comes from a few metres to a few hundred metres, except that in karst systems it could be even higher (Przylibski, 2000a, 2005; Przylibski et al., 2001) (Table 4). As a rule then, what should be emphasized is that radon reaches a groundwater intake from its immediate neighbourhood, travelling together with water, from a few to a few hundred metres at the time no longer than 38 days. By far the highest number of ^{222}Rn atoms are released into water very close to the intake – usually at the distance of a few meters from the intake. ^{222}Rn atoms dissolved at a further distance (earlier) undergo radioactive decay before the groundwater reaches the intake. Therefore, what has to be stressed is that its activity concentration in water in the intake is determined by the geology and mineral (and chemical) composition of the rocks in the immediate vicinity of the well, borehole or spring.

Radon content in surface water depends, among other factors, on partial pressure of this gas over water – in the atmosphere. As it is very small in the atmosphere – ^{222}Rn activity concentration in the air over mainland, at the height of 1–2 m over the ground is usually from a few to about a dozen Bq m^{-3} (Cothern and Smith, 1987; Nevissi and Bodansky, 1987; Jagielak et al., 1998; Kataoka et al., 2003; Sesana et al., 2003; Nagaraja et al., 2003 etc.), hence also radon concentration in surface water normally does not exceed several or at most a few dozen Bq dm^{-3}. The concentration depends chiefly on the type of rocks building the bed and the sides of a stream or river (Przylibski, 2005). Therefore, if groundwater in an intake (well, spring or borehole) comes in contact with the atmosphere, then ^{222}Rn activity concentration in this water decreases significantly and, as a rule, does not pose any threat at all. However, in professionally constructed groundwater intakes, water does not usually have contact with the atmosphere and it is supplied to a building (private intake) or a pipe network (public intake) with almost all ^{222}Rn atoms that have reached the intake with groundwater. Only a small number of radon atoms undergo natural radioactive decay and do not reach consumers, unless the pipeline and reservoir network is very large, like e.g. in big cities.

The above facts indicate that the highest concentrations of radon could be expected in groundwaters drawn from ^{226}Ra-enriched reservoir rocks, which are characterised by high emanation coefficient. ^{222}Rn atoms reach an intake from its immediate neighbourhood, and if the groundwater in the intake does not come in contact with the atmospheric air, a large number of radon atoms may then reach households.

The highest emanation coefficient is characteristic of reservoir rocks which have a dense crack network or/and high porosity and are vulnerably exposed to weathering processes, both physical and chemical. Physical weathering plays an important part in rock fragmentation, as it results in increasing the volume of pores and fissures which enable groundwaters to circulate freely. Chemical weathering, on the other hand, besides further fragmentation of mineral components, enables the precipitation of secondary minerals (chemical compounds) containing ^{226}Ra atoms in pores and fissures. In such a case, the process of ^{222}Rn atom emanation into groundwaters filling pores and fissures is additionally intensified – the emanation coefficient is significantly higher. The crack network is much denser, which also contributes to increasing the emanation coefficient when reservoir rocks lie in tectonic deformation zones – close to faults, tectonic thrusts, etc. The role of tectonic deformations in this context has been emphasized in many publications (e.g. Choubey et

Table 3. Percentage part of ^{222}Rn atoms produced as a result of the decay of $^{226}Ra^{2+}$ ions dissolved in groundwater in total ^{222}Rn atoms dissolved in groundwater of selected intakes in the Sudetes. These values are presented together with the information on ^{222}Rn and ^{226}Ra activity concentrations and TDS values for these groundwaters (according to Przylibski, 2005).

Intake	TDS	^{222}Rn	^{226}Ra	^{226}Ra/^{222}Rn
	[g m^{-3}]	[Bq m^{-3}]		[%]
IZERA MASSIF CZERNIAWA-ZDRÓJ				
nr 4	2802	35 100	780	2.22
P-2	2125	15 900	790	4.97
IZERA MASSIF ŚWIERADÓW-ZDRÓJ				
Górne A	289	441 100	46	0.01
1A	683	86 800	525	0.61
2P	1984	21 000	778	3.71
INTRA-SUDETIC BASIN SZCZAWNO-ZDRÓJ				
Marta	2319	215 700	706	0.33
Młynarz	2291	32 300	77	0.24
Mieszko	3025	31 200	135	0.43
Mieszko-14	701	9600	53	0.55
INTRA-SUDETIC BASIN KUDOWA-ZDRÓJ				
K-200	3456	7200	640	8.89
nr 2 Moniuszko	3436	5500	110	2.00
nr 3 Nowy Marchlewski	1699	59 200	70	0.12
Górne	2367	18 700	160	0.86
ŚNIEŻNIK MASSIF LĄDEK-ZDRÓJ				
Chrobry	201	137 100	10	0.007
Dąbrówka	199	127 700	11	0.009
Jerzy	188	1 109 000	88	0.008
L-2 (Zdzisław)	208	117 100	12	0.010
Skłodowska-Curie	199	329 500	26	0.008
Wojciech	202	218600	15	0.007
ORLICA MASSIF DŁUGOPOLE-ZDRÓJ				
Emilia	910	108 500	90	0.08
Renata	1218	68 800	100	0.15
Kazimierz	937	65 300	120	0.18

al., 2007; Przylibski, 2005, 2007; Przylibski et al., 2001). Such zones are usually also perfect paths for groundwater migration.

The above characteristics of reservoir rocks of groundwaters containing increased concentrations of radon (radon waters, high-radon waters and extreme-radon waters) enable characterizing their general type. These are waters of shallow circulation (up to several dozen metres below ground level) and contemporary infiltration, i.e. with underground flow time ranging from several days to a few or a few dozen years. Owing to their underground flow time, these are usually also poorly-mineralised waters (total dissolved solids – TDS is usually <0.2–$0.5\,g\,dm^{-3}$) (Fig. 3). Their resources are renewable, however, due to their small depth, short underground flow time and contact with the surface of the lithosphere and the atmosphere, these waters are also vulnerable to contamination.

The above characteristics of groundwaters which could potentially be radon waters, high-radon waters or extreme-radon waters, result mostly from recognising the influence of the emanation coefficient of reservoir rocks on ^{222}Rn activity concentration in groundwaters. Also, taking into consideration the influence of ^{226}Ra content in reservoir rocks, one should conclude that groundwaters flowing from ^{226}Ra-enriched rocks will obviously exhibit an increased concentration of ^{222}Rn. However, for the same reservoir rocks, waters

Table 4. The distance of ^{222}Rn atoms transport with groundwater to the intake (L) and the discharge of the intake (Q) for selected wells and boreholes in the Sudetes (according to Przylibski, 2005).

Intake	Q $[m^3 d^{-1}]$	L [m]
IZERA MASSIF ŚWIERADÓW-ZDRÓJ		
1A	19.9	16
2P	5.3	6
INTRA-SUDETIC BASIN SZCZAWNO-ZDRÓJ		
Marta	1.0	3
Mieszko	8.0	8
INTRA-SUDETIC BASIN POLANICA-ZDRÓJ		
Wielka Pieniawa	446.4	32
INTRA-SUDETIC BASIN GORZANÓW		
nr 5	1 157.0	13
nr 1 (Złota Kaczka)	388.0	63
KARKONOSZE GRANITE CIEPLICE ŚLĄSKIE-ZDRÓJ		
nr 2 Sobieski	4.5	10
nr 4 Nowe	89.0	43
KARKONOSZE GRANITE SZKLARSKA PORĘBA		
nr 1	89.0	38
nr 6	29.0	22
KAMIENIEC METAMORPHIC BELT PRZERZECZYN-ZDRÓJ		
nr 2	89.0	57
nr 9	89.0	16
ŚNIEŻNIK MASSIF LĄDEK-ZDRÓJ		
Chrobry	55.0	19
Jerzy	380.0	49
ŚNIEŻNIK MASSIF KAMIENICA		
Śnieżnik adit	1 930.0	110
K6	360.0	67
ŚNIEŻNIK MASSIF KLETNO		
Kletno I spring	2 720.0	271*
Romanowskie 1 spring	1 700.0	214*

* karst groundwater

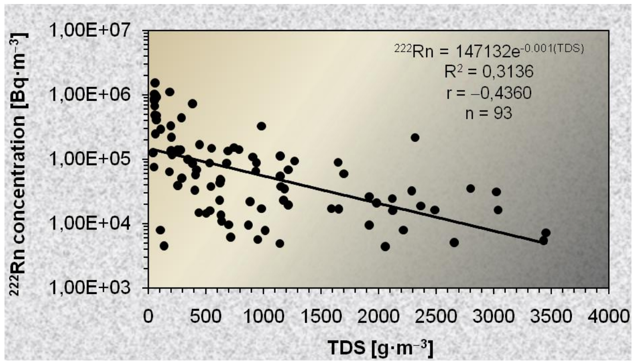

Fig. 3. Correlation between ^{222}Rn activity concentration in groundwater and the mineralization (Total Dissolved Solids) of the groundwater for the 93 selected intakes and springs of the Sudetes (SW Poland) (according to Przylibski, 2005).

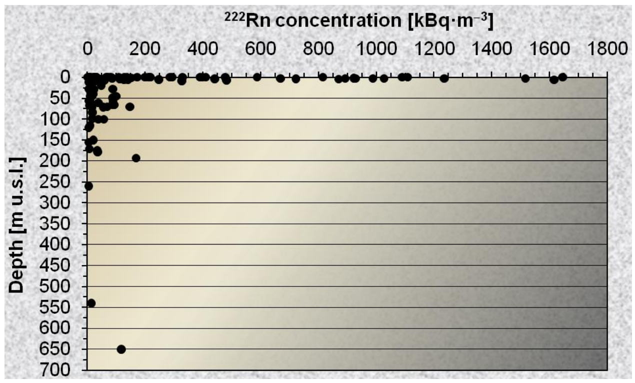

Fig. 4. Correlation between ^{222}Rn activity concentration and the depth of groundwater intake for the 111 selected intakes from the area of the Sudetes (SW Poland) (according to Przylibski, 2005).

with the highest ^{222}Rn activity concentration will circulate in and flow out of zones with an increased emanation coefficient, i.e. from cracked and weathered rocks in the near-surface part of the lithosphere.

The practical relevance of the above discussion and the ensuing conclusions has been confirmed by the author's study of over 100 groundwater intakes in the area of the Sudetes (SW Poland) (Przylibski, 2005). It demonstrated that the highest emanation coefficient is characteristic of rocks lying in the weathering zone, to the depth of 30–50 m below ground level. The highest values of ^{222}Rn activity concentration are recorded in groundwaters drawn from these rocks. They increase with the rise in ^{226}Ra content in reservoir rocks. At large depths, even a high content of ^{226}Ra in reservoir rock does not cause the formation of high values of ^{222}Rn activity concentration in the groundwater flowing through it (Fig. 4). This regularity has been presented before for a smaller number of analysed groundwaters (Ciężkowski and Przylibski, 1997).

It is also noteworthy that the groundwaters that can potentially contain dangerously high ($\geq$100 Bq dm^{-3}) radon concentrations, i.e. radon waters, high-radon waters and extreme-radon waters, are all groundwaters whose resources are the easiest to be drawn for household use and for consumption. They are often the main source of water supply for individual households and, through private intakes, they often supply one or a few families (houses). More rarely, such groundwaters are drawn from public intakes. Deradoning of such waters in an intake is relatively simple and does not require installing any complicated equipment, so the cost of this process is also low compared to the cost of a building or even the cost of a water intake itself. Having in mind the risk of developing a lung tumour related to household use of waters containing increased radon concentration, bearing the expenses of de-radoning water in an intake seems reasonable and well-grounded.

3 Conclusions

Waters that can potentially contain the highest ($\geq$100 Bq dm^{-3}) hazardous contents of dissolved radon are groundwaters of shallow circulation (to the depth of several dozen metres below ground level) and contemporary infiltration, i.e. with underground flow time of a few days or a few fortnights and a few years to a few decades. In terms of underground flow time, these are mostly also poorly mineralised waters (TDS$<$0.2–0.5 g dm^{-3}). Their resources are renewable, but due to the small depth and short underground flow time, as well as contact with the surface of the litosphere and the atmosphere, these waters are also vulnerable to contamination. Based on the content of ^{222}Rn dissolved in them, these waters should be classified as radon waters, high-radon waters and extreme-radon waters.

Such waters are usually drawn from private intakes and are intended for consumption and household use, usually in one or at most a few buildings. More rarely, such waters are drawn from public intakes. This is why these are largely owners of private groundwater intakes who are the most exposed to radon exhalation from waters used in households, and consequently – to obtaining a higher dose of ionising radioactivity from radon and its radioactive daughters. This situation is particularly disadvantageous, as the cost of removing radon from waters drawn from several or several dozen intakes in one town or village is higher than in the cost of de-radoning water in one big public intake.

In conclusion, it seems necessary to take practical, and in some countries also legislative steps, modelled on regulations introduced earlier in some other countries. They should be aimed at introducing compulsory measurements of ^{222}Rn activity concentration chiefly in groundwaters of shallow circulation and contemporary infiltration, especially those drawn from small private intakes – individually dug wells or shallow drilled wells (up to several dozen metres below ground level). These waters, in any circumstances, will contain locally (in an area with the same geological structure – within one lithostratigraphic unit) the highest radon concentration. Using these water resources (radon waters, high-radon waters and extreme-radon waters) in many cases probably requires and will require removing at least some radon from groundwater when still in the intake, i.e. before supplying it to the piping network, or directly to a building, in case of a private intake.

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