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SIZE ESTIMATION AND PROTECTION OF THE AREAS SUPPLYING RADON TO GROUNDWATER INTAKES

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SZACOWANIE WIELKOŚCI ORAZ OCHRONA OBSZARÓW ZASILANIA RADONEM UJĘĆ WÓD PODZIEMNYCH

W pracy scharakteryzowano metodę szacowania wielkości obszarów zasilania radonem ujęć podziemnych wód radonowych. Jako przykładowe wybrano ujęcia wód radonowych i szczaw radonowych Lądka Zdroju, Świeradowa Zdroju i Kowar. W wyniku przeprowadzonych obliczeń wykazano, że objętość skał zasilających radonem wody podziemne poszczególnych ujęć waha się w granicach od kilkunastu do kilkuset tysięcy metrów sześciennych. Po uwzględnieniu głębokości strefy nasycania tych wód radonem obszar zasilania ujęć tym gazem ma powierzchnię od kilkuset do kilku tysięcy metrów kwadratowych. Największymi obszarami zasilania radonem-222 charakteryzują się ujęcia o najwyższej wydajności, najmniejszymi zaś ujęcia o niewielkich wydajnościach, a zwłaszcza ujęcia mieszaniny wód podziemnych, z których tylko jedna składowa dostarcza znacznych ilości radonu-222. Obszary zasilania wód podziemnych, w których rozpuszcza się radon, leżą z reguły w znacznej odległości od ujęć i nie pokrywają się z obszarami zasilania ujęć tych wód w radon-222. Obecnie istotne wydaje się niewielkie rozszerzenie istniejących stref bezpośredniej ochrony ujęć, które to strefy w zupełności zabezpieczyłyby zasoby radonu-222 poprzez ochronę naturalnej porowatości efektywnej skał w obszarze zasilania ujęć tym gazem.

Summary

The paper characterises the method of estimating the size of the areas supplying radon to radon groundwater intakes. It is presented on the example of the intakes of radon groundwaters and radon acidulous waters of Lądek Zdrój, Świeradów Zdrój and Kowary. The results of appropriate calculations prove that the volume of rocks supplying radon to the groundwaters of particular intakes oscillates from over ten to several hundred thousand cubic metres. Considering the depth of the zone where radon saturation of these waters takes place, the area supplying this gas to particular intakes varies from several hundred to several thousand square metres. The largest areas of radon-222 supply are characteristic of the most discharge springs, while the smallest ones belong to the springs of low discharge, especially the intakes of groundwater mixture, where only one component supplies large quantities of radon-222. The recharge areas of groundwaters in which radon is dissolved are usually quite remote from the intakes and are not identical with the areas supplying these waters with radon-222. Currently, it seems to be important to extend slightly the existing zones of direct protection of the intakes, which could entirely safeguard the reserves of radon-222 through the protection of natural effective rock porosity in the area supplying the intakes with this gas.

INTRODUCTION

Groundwaters containing enhanced concentrations of radon and/or radium described as so-called specific components [30] can be recognised as medicinal in light of binding regulations. By virtue of Geological and Mining Law, medicinal waters have been classified as mineral products [35]. A decree of the Council of Ministers has defined the deposits of groundwaters recognised as medicinal and most of them were classified as basic mineral products. They include, among others, deposits of radioactive waters and radioactive acidulous waters of Czerniawa Zdrój, Świeradów Zdrój, Szczawno Zdrój, Kudowa Zdrój, Lądek Zdrój and Przerzeczyn Zdrój [42]. All these places are situated in the Sudety Mountains or at their foot (Przerzeczyn Zdrój). Except for these, there are also other groundwaters that meet the criteria allowing their classification as radioactive medicinal waters. One of these criteria is the radioactivity exceeding 2 nCi/dm^3 (74 Bq/dm^3), which should be understood as the content of radon and/or radium above this value [30, 41]. Among such waters one can also include the waters recognised as medicinal for other reasons, extracted e.g. in Długopole Zdrój, Duszniki Zdrój and Cieplice Śląskie Zdrój, and many other groundwaters not qualified as medicinal that are found in many places e.g. in the area of the Karkonosze granite, including Kowary and Szklarska Poręba [9, 18 – 20, 36, 37].

The application of radioactive treatments (mostly inhalations and baths, but also drinking therapy) is justified by some scientists' notions of so-called "radiation hormesis" phenomenon, according to which small doses of radiation have a curative effect on many diseases. These treatments use mostly radioactive waters and radon – the radioactive gas discharged from these waters. However, the direct medicinal agent is not the water itself, but the discharged radon together with its decay products, radioactive isotopes of polonium, lead, bismuth and thallium [28, 29, 31, 32, 34, 48].

Owing to their application, medicinal groundwaters are the object of special protection. However, what is particularly important is not only the protection of the quality and reserves of the groundwater itself, but also of the substances dissolved in this water that are used as curative agents. In the conditions of long underground flow time and gradual enrichment of water with dissolved components of the reservoir rocks, the protection of both the medium and medicinal components are strictly interrelated. In the case of a gaseous component of medicinal radioactive waters, such as radon, protection of the reserves and of the quality of the medium (the groundwater) does not have to be sufficient for the protection of radon reserves.

OUTLINE OF RADON GEOCHEMISTRY IN GROUNDWATERS

Radon-222 produced as a result of radioactive alpha decay of nuclide ^{226}Ra, as a gas exhibits a natural tendency to be released from the structure of the minerals and rocks where it is generated. During its migration towards land surface, it is easily dissolved in groundwaters. The most important conditions for the presence of radon in groundwaters are an increased concentration of radium in the reservoir rocks and the enhanced emanation coefficient of these rocks. The latter depends mainly on the amount of cracks and fissures and on how much they are interconnected, i.e. on the effective porosity. In some cases the high emanation coefficient is particularly important and despite low radium content in the rocks it can be the reason for considerably increased radon concentrations in groundwaters. On the other hand, neither the duration of groundwater-rock contact nor the majority of the dissolved components (including radium) have influence on the recorded values of radon concentrations in these waters. A relatively small depth of radioactive water circulation (predominantly from 20 to 50 metres, more rarely up to ca. 200 m below the ground level) is related to the significant influence of the emanation coefficient, which is the highest in the near-surface sections of the earth's crust. This factor, as well as the short half-life of radon ($T_{1/2}$ of the most stable isotope, ^{222}Rn, equals ca. 3.82 days), are the causes why radon, whose concentration is measured in the intake, dissolves in groundwaters in their outflow zone. It can be also transported to more highly mineralised waters of deep circulation (e.g. acidulous waters) with infiltration waters of shallow circulation that dilute them. The amount of radon dissolved in groundwaters can depend on the presence of better soluble carbon dioxide (in acidulous waters), as well as on the physical parameters of the water (pH and temperature), and on atmospheric factors (pressure, temperature and humidity) [1, 10–12, 23, 27, 36–40].

OBJECTS OF INVESTIGATIONS

Fig. 1 presents the position of the objects selected for investigation. These are groundwater intakes containing considerable concentrations of radon (Tab. 1). Radon supplying areas were estimated for the following intakes of medicinal groundwaters: Maria Skłodowska-Curie intake (MCS) and Górne intake in Świeradów Zdrój, Chrobry, Dąbrówka, Jerzy, Skłodowska-Curie and Wojciech intakes in Lądek Zdrój, and also for the groundwaters flowing out of intake no. 26 in Kowary. The waters from the latter intake had been regarded as medicinal until 1994.

Świeradów Zdrój is a spa situated in the area of so-called Karkonosze--Izera block, a large geological unit of the western Sudety Mts. It is composed of two basic parts: the granitoid Karkonosze massif and its metamorphic

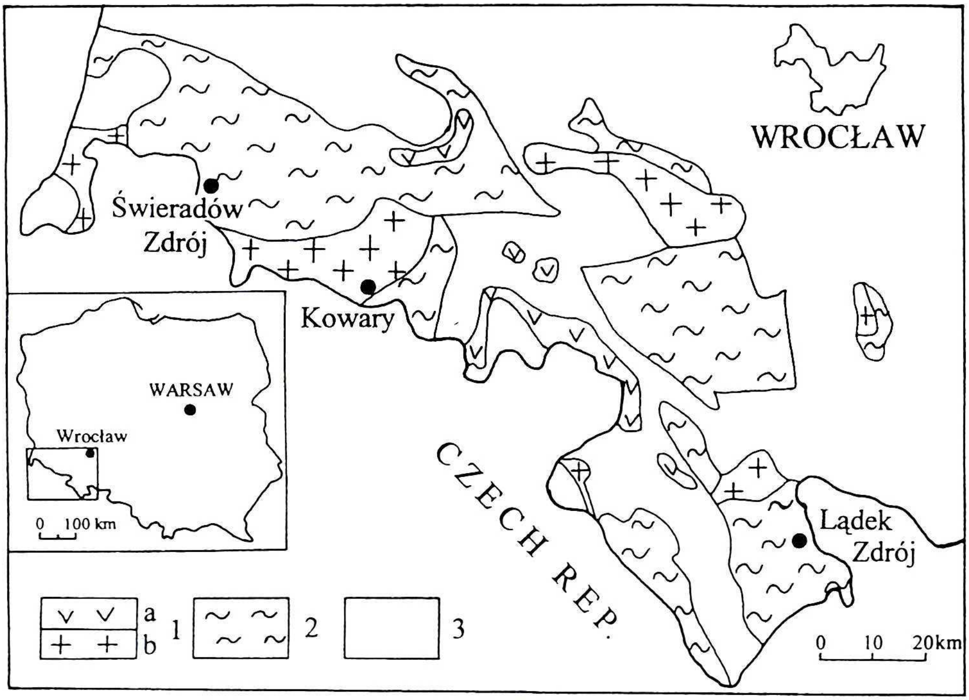

Fig. 1. Position of selected research objects on the background of a geological sketch of Lower Silesia:

1 – igneous rocks (a – effusive, b – plutonic); 2 – metamorphic rocks; 3 – sedimentary rocks

cover. The surroundings of Świeradów Zdrój are built of the rocks of the metamorphic cover. In this area there are different varieties of gneisses, granite-gneisses and schists. Among these rocks there are also minor inclusions of vein rocks (aplites, quartzite veins, amphibolites). The age of the rocks in this complex has been specified as Precambrian. Owing to the mountainous character of relief in this area, these deposits lie only under a light overlayer of Quaternary deposits (clays and slope debris, river-valley sands and gravels, peats). Among the metamorphic rocks one can distinguish two dislocation directions of NW-SE and NE-SW patterns (Fig. 2). The main fault in this region is the so-called spring fault of Świeradów with NW-SE orientation, which is disrupted by numerous transverse dislocation of NE-SW pattern. Fault surfaces, and particularly the places of their intersection, are considered the basic areas of medicinal water circulation in the Izera block [4, 5, 15, 17, 21, 22, 47, 50, 52, 53].

In Świeradów Zdrój two types of waters are extracted for balneological purposes: poorly mineralised radioactive waters of shallow circulation and radioactive acidulous waters. The physico-chemical character of the latter is the result of mixing acidulous waters, whose chemical composition formed at

Table 1. Volume of the rocks supplying radon to selected groundwater intakes of the Sudety Mountains and selected characteristic parameters of these waters and their reservoir rocks

Radon-222 concentrations used for calculating the mean value were measured in 1963–1998. Mean discharge quoted from the decision of the Hydrogeological Documentation Committee corroborating the resources of particular intakes

Locality	Intake	Mean content of ^{222}Rn (number of measurements)	Mean discharge	Porosity of reservoir rocks	Volume of the rocks supplying radon-222 to the groundwater intake
		[Bq/dm³]	[m³/day]	[–]	[m³]
Świeradów Zdrój	MCS	885 (40)	103.2	0.04	98 600
	Górne	525 (1300)	21.6	0.04	17 400
Lądek Zdrój	Chrobry	119 (920)	55.2	0.04	52 700
	Dąbrówka	136 (835)	26.4	0.04	25 200
	Jerzy	1235 (3550)	379.2	0.04	362 100
	Skłodowska--Curie	213 (760)	84.0	0.04	80 200
	Wojciech	166 (695)	120.0	0.04	114 600
Kowary	nr 26	520 (4)	21.6	0.04	20 600

large depths, with shallow radioactive waters [4, 5]. These acidulous waters contain free carbon dioxide, whose presence is related to the final manifestations of the Tertiary volcanism. Such a notion has been corroborated by the examination results of the isotope composition of carbon in the carbon dioxide [14].

Currently, radioactive waters are extracted from Maria Skłodowska-Curie (MCS) intake consisting of six wells from 2.5 m to 6.5 m deep [43]. They are situated within leucogranites and granite-gneisses [17, 21]. At the same time acidulous waters are exploited from Górne and 1A intakes and were formerly exploited in 2P and Zofia intakes. They represent generally type HCO_3–Ca–(Mg), Rn. In all the mentioned intakes these waters flow out from gneisses and granite--gneisses. In Górne intake acidulous waters are extracted in three wells from 6 to 10 m deep. They are communicating hydraulically and their total productivity amounts to 0.5 m^3/h, with the productivity of well no. 3 higher than the total productivity of wells 1 and 2, which are comparable [17, 43].

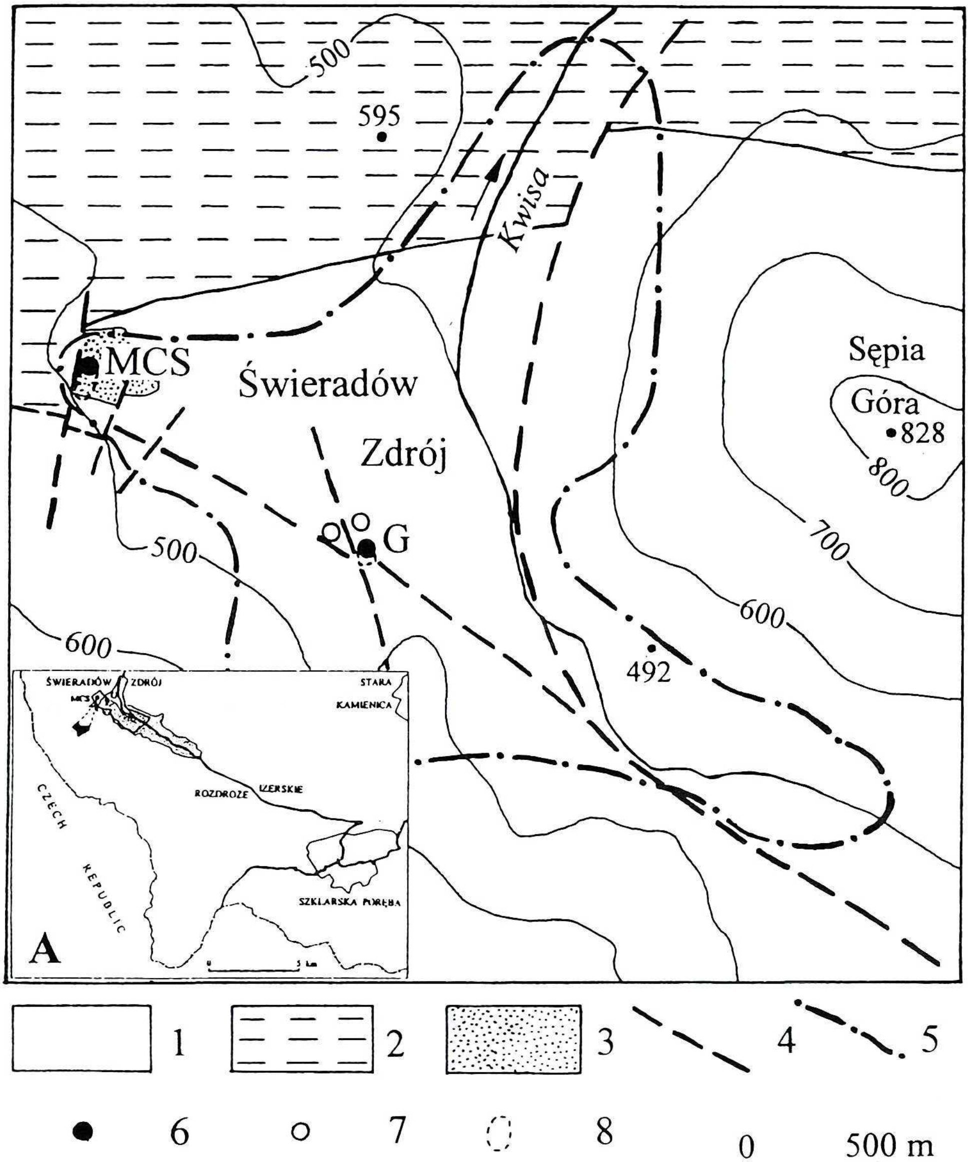

Fig. 2. A simplified geological sketch of Świeradów Zdrój area with plotted intakes of the examined medicinal waters (after [17, 47]):

1 – gneisses and granite-gneisses, 2 – mica schists, 3 – leucogranites, 4 – faults, 5 – the boundary of the urban area of Świeradów Zdrój, 6 – intakes of the examined medicinal waters (MCS – Maria Skłodowska-Curie intake, G – Górne intake), 7 – other exploited intakes of medicinal waters, 8 – presupposed radon-222 supply areas

In sketch A the recharge areas of Górne intake (dotted area) and Maria Skłodowska-Curie intake (striped area) have been plotted according to [8]

The results of isotope examinations prove that the medicinal waters of Świeradów Zdrój are of diversified age. The underground flow time of the tritium component of the waters from Górne intake has been estimated at ca. 90 years. Much a shorter underground flow time is characteristic of the waters in MCS intake, whose age could be estimated at ca. 5 years [8].

The recharge area of the radioactive waters of Świeradów Zdrój (MCS intake) encloses the northern and north-eastern slope of Stóg Izerski, ca. 2 km straightaway from the intake. At the same time, the acidulous waters extracted in Świeradów Zdrój are recharged from the upper tract of the Kwisa valley, the southern and eastern slopes of Sępia Góra, and the northern and north-eastern foothills of Stóg Izerski, together with the spa situated in this area. The intakes of acidulous waters lie in their recharge area, which extends over the distance of ca. 5 km from particular intakes (Fig. 2) [8].

The radon found in the medicinal waters of Świeradów Zdrój is generated in the granite-gneisses and leucogranites building the immediate neighbourhoods of the intakes, which are also their recharge areas. Intensive radon formation is related to the increased content of ^{226}Ra nuclide in both types of rock. The process of intensive radon dissolution in groundwaters takes place mainly at the depths from several to several ten meters below the ground level and is caused by the enhanced emanation coefficient. This results from the fact that rocks in this zone are remarkably affected by weathering processes and they are also cut by faults and fissures [10, 39]. Radioactive waters mix up with acidulous waters of deep circulation thus forming rare radioactive acidulous waters [4, 5].

Lądek Zdrój is situated in the area of Lądek – Śnieżnik metamorphicum, which is the eastern part of the Orlica – Śnieżnik dome. It is the easternmost geological unit of the western Sudety Mts. In the west the metamorphicum borders on the Upper Nysa Rift, which separates it from the western part of the Orlica – Śnieżnik dome, i.e. the crystallinicum of the Bystrzyckie and Orlickie Mountains. In the north-east it is bounded by the Sudetic marginal fault, while in the north-west it borders on the granitoid Kłodzko – Złoty Stok intrusion. The eastern and southern boundary is marked by the Ramzova thrust, separating the eastern and western Sudety Mts [13, 33].

The geological structure of Lądek Zdrój area is composed mainly of Proterozoic-Palaeozoic crystalline rocks. They include rocks of the schist Stronie series (mica schists, marbles, amphibolites, amphibolite schists, quartzites, erlans and others), Gierałtów gneisses (microclinised plagioclase gneisses, migmatites, oligoclase-microcline gneisses with biotite, quartz-plagioclase gneisses) and Śnieżnik gneisses (coarse-grained, augen, with diverse structure and texture). All these rocks were formed as a result of polymetamorphic and polycyclic evolution of the supracrustal series. The least transformed are the Stronie schists and the most – the Gierałtów gneisses. In the Carboniferous period an intrusion of granitoid magmas took place, which resulted in the formation of lamprophyre and quartz veins in the Lądek area. In the late Tertiary into

Quaternary periods the volcanic activity also occurred in this area. This is when basaltoid veins and domes were formed. In river and stream valleys Tertiary and Quaternary sediments are found. Their thickness is smaller on hill slopes and tops, which are covered by slope waste-mantle (Fig. 3) [21, 24–26].

In the Lądek area one can distinguish two anticlinoria: the Gierałtów and the Radochów ones, separated by the Lądek–Travna synclinorium. In their area one can observe numerous discontinuous dislocations, which are the routes of groundwater flow. They have the NW-SE direction and are perpen-

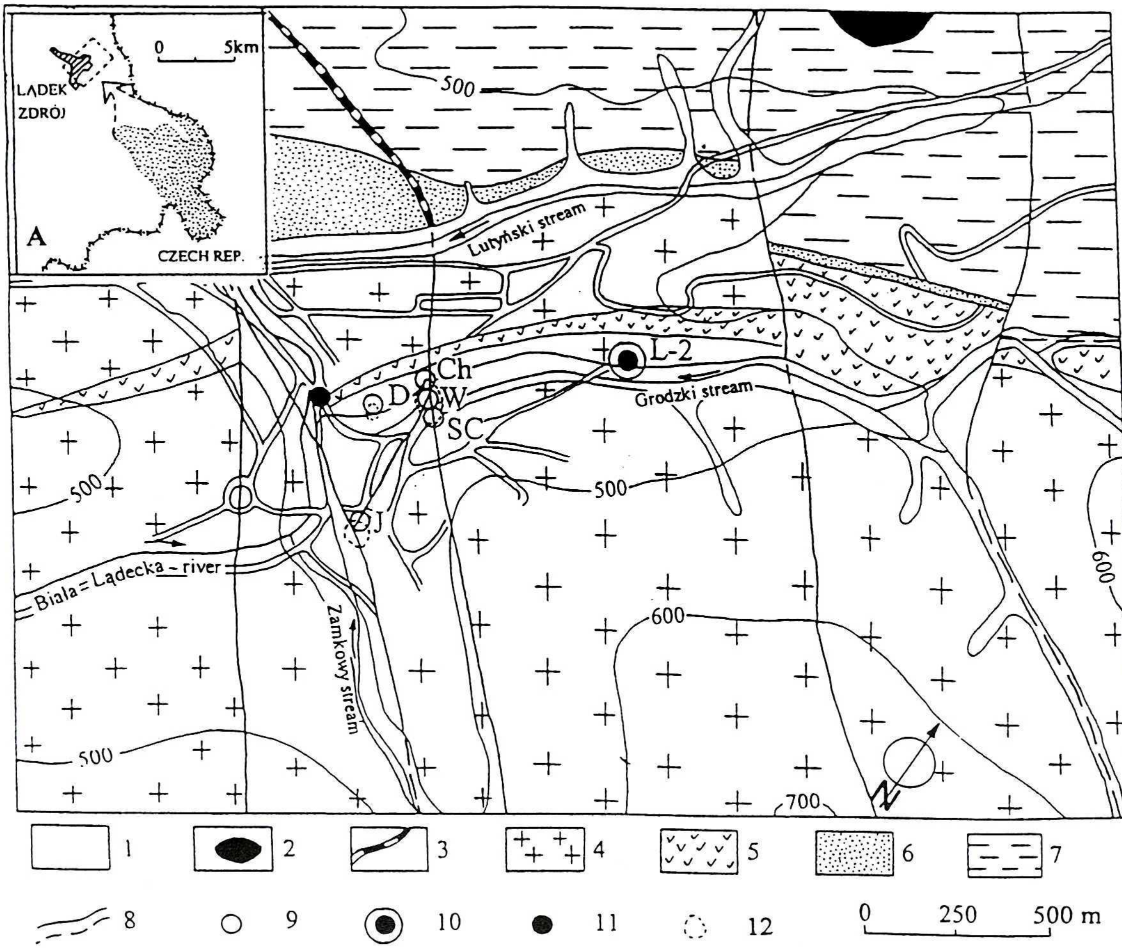

Fig. 3. A simplified geological sketch of Lądek Zdrój area with plotted intakes of the examined medicinal waters (after [26]):

1 — alluvial deposits, 2 — basalts, 3 — lamprophyres, 4 — Gierałtów gneisses, 5 — Śnieżnik gneisses, 6 — mylonites, 7 — schists of the Stronie series, 8 — faults, 9 — chief medicinal springs (D — Dąbrówka, J — Jerzy, Ch — Chrobry, W — Wojciech, SC — Skłodowska-Curie), 10 — L-2 borehole, 11 — other intakes of medicinal waters, 12 — presupposed radon-222 supply areas

In sketch A the recharge area of Lądek Zdrój medicinal waters has been dotted; the arrow marks the flow direction of these waters according to [7, 54] dicular to the tectonic units mentioned above. The network of these faults is particularly dense in Lądek Zdrój area, where they are 200 – 400 m away from one another (cf. Fig. 3) [21, 24 – 26].

The water-bearing deposits of the medicinal waters of Lądek Zdrój are Gierałtów gneisses of varied facies. The waters are fissure waters of deep circulation. All the intakes of thermal waters in Lądek Zdrój (Jerzy, Wojciech, Dąbrówka, Chrobry and Skłodowska-Curie springs, and the L-2 borehole) are recharged by the waters from one deposit. It is poorly mineralised sodium-bicarbonate, radioactive, fluoride and sulphide thermal water type $HCO_3 - F - Na$. The whole formation process of these waters takes place in the source structure enclosed within the Lądek – Śnieżnik metamorphicum. The depth of this structure can be estimated at ca. 2000 – 2500 m. After infiltration of these waters in the recharge area, which is situated in the Bialskie Mountains and the southern part of the Złote Mountains, the water flows at large depths in the NW direction along big dislocation zones of NW-SE orientation. This is where its chemical composition and physical properties are formed. Natural water outflows from the depth of the structure arise along the Lądek Zdrój fault, which is transverse to the dislocation zones mentioned above. On the other hand, outflows of water in the form of springs are related again to the faults of the Sudetic orientation (NW-SE) and they occur at the fork of the faults. The origin of radon in the medicinal waters of Lądek Zdrój is related to the near-surface (up to ca. 50 m deep) rock layers, where owing to the increased emanation coefficient the produced radon is dissolved in the waters flowing out to the surface. To much a smaller degree radon is supplied to these waters by the admixture of plain infiltration waters of shallow circulation, which dilute deep thermal waters. One should emphasise a particularly high concentration of radon in the waters of Jerzy intake, which results from its position at the fork of dislocation zones. It enables increased dissolving of radon in the mixture of thermal waters and shallow infiltration waters flowing to the surface [2, 3, 5, 21, 24 – 26, 40, 49, 51 – 54].

Isotope examinations and establishing the content of noble gases have made it possible to determine the age of the medicinal waters of Lądek Zdrój. It has been estimated at ca. 9000 years [5, 7, 54].

The radioactive waters of Kowary are poorly mineralised, with overall mineralisation of ca. 73 mg/dm^3 and the content of radon from 390 to 650 Bq/dm^3. Slight temperature fluctuations indicate recharging of this spring by waters of deep circulation. The discharge has been estimated at 0.9 m^3/h [18]. The water flows out as a fissure spring at the contact of an aplite vein with coarse-grained, porphyraceous Karkonosze granite, which is heavily weathered. The area in question is situated in the contact zone of the Karkonosze granite with the rocks of its south-eastern metamorphic cover, which in this region is composed of Kowary gneisses with insertions and lenses of skarns and granite-gneisses (Fig. 4) [46]. The directions of granite fissuring often form communicating fissure systems, which reach considerable depths and form quite regular patterns at large distances. These fissures are abundant water reservoirs [18]. Such a structure of the groundwater reservoir is corroborated by the dispersion flow model of the waters from spring no. 26, obtained by analysing the content of tritium in these waters [6].

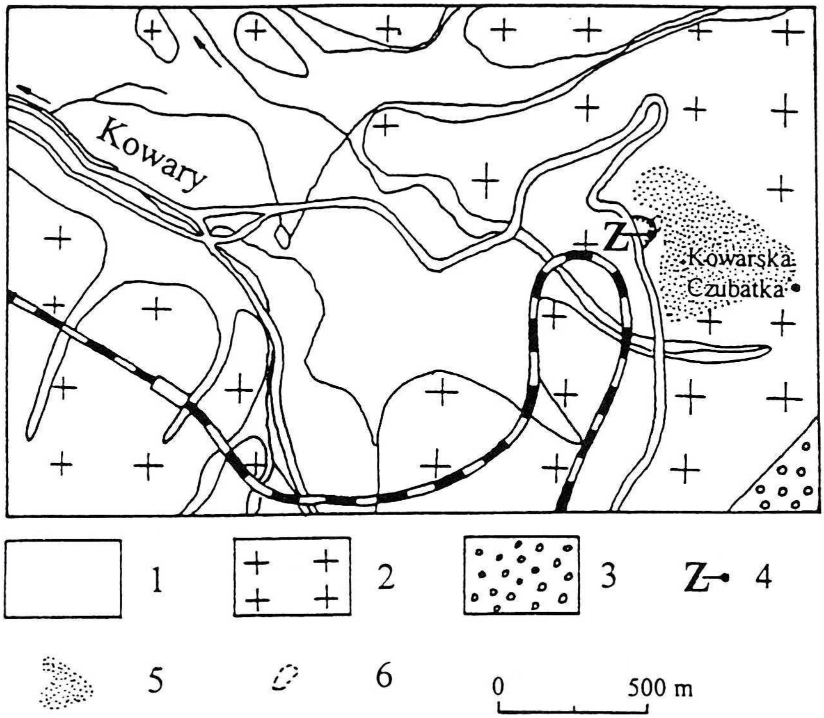

Fig. 4. A simplified geological sketch of Kowary area (after [46]):

1 – quaternary deposits, 2 – porphyraceous coarse-grained granites, 3 – augen gneisses, 4 – spring no. 26 in Kowary, 5 – recharge area of the radon groundwaters discharged in spring no. 26 after [6], 6 – presupposed radon-222 supply area of spring no. 26

The age (average underground flow time) of the groundwaters from spring no. 26 in Kowary has been estimated on the basis of tritium content at ca. 15 years. The recharge area of this intake has been determined by means of isotope examinations (stable isotopes of oxygen and hydrogen). It encompasses the western slopes of Kowarska Czubatka in the Rudawy Janowickie Mts. and is ca. 300 m straightaway from the spring. It is built of coarse-grained porphyraceous granites, which are fissured and cut by aplite veins [6, 46].

The presence of high concentrations of radon-222 measured in the waters of the fissure spring no. 26 in Kowary is not a result of the decay of its parent nuclide (^{226}Ra) dissolved in these waters. Radon dissolves in the waters flowing through a narrow contact zone between aplite and granite, the rocks where it is produced as a result of radium-226 decay. The only atoms of radon that can reach the water outflow are those which dissolve no further than several ten to a hundred and several ten metres away from the spring [38].

METHODS OF INVESTIGATIONS

The archival results of content determination of radon in the waters (expressed in nCi/dm^3 and converted by the author to Bq/dm^3) used in the paper come from the archives of the Resort Mining Institutes of Lądek Zdrój, Świeradów Zdrój and Cieplice Śląskie Zdrój. They were obtained by the employees of the resort laboratories of Lądek Zdrój and Świeradów Zdrój and the laboratory of B.P.iU.T.B.U. Balneoprojekt in Szczawno Zdrój. The concentration of radon, extracted to the gaseous phase, was measured with a Soviet ionisation chamber (SG-11 M) using the electrostatic effect of ionised air on a quartz thread. The accuracy of this method reaches 0.1 nCi/dm^3 (3.7 Bq/dm^3).

The calculation of the volume of the rocks that supply radon to a groundwater intake can be based on simple relationships between the effective porosity of the rocks, their density and emanation coefficient [37]:

$$V = m/(d \cdot K_{em}), \tag{1}$$

where:

V – volume of the rocks supplying radon to the groundwater intake,
m – weight of the rocks supplying radon to the groundwater intake,
d – density of the rocks supplying radon to the groundwater intake,
K_{em} – emanation coefficient of the rocks supplying radon to the groundwater intake.

However, there are a number of parameters, especially when it comes to calculating the emanation coefficient of rocks, which cannot be measured precisely in the field and whose variability in space is so large that even laboratory tests do not bring fully satisfactory results. In that case, it is possible to use much simpler method of defining the volume of rocks supplying radon to a given groundwater intake.

Knowing the diurnal discharge of the intake (Q), it is possible to calculate the volume (V_s) of the water remaining in the system that has been recharging the intake for the last 38.2 days. This period is practically the maximum time after which radon-222 can be still registered in the waters flowing out of the intake. This time equals ten half-lives of ^{222}Rn nuclide. After this period there remains mere 0.098% of the initial amount of radon. This allows an assumption that the intake where radon-222 concentration is measured is reached only by these radon atoms that were formed and dissolved in the water flowing to the intake no sooner than 38.2 days before the measurement in this intake. We can calculate V_s with the use of a simple formula:

$$V_s = Q \cdot 38.2, \tag{2}$$

where:

V_s – volume of the water that remains in the system recharging the intake for the last 38.2 days [m^3],
Q – diurnal discharge of the intake [m^3 per day].

By dividing the obtained result (V_s) by the effective porosity of the reservoir rocks (P) we will obtain the volume of the reservoir rocks that hold the given volume of groundwater (V_s), i.e. the volume of the rocks supplying radon to the groundwater intake in question (V_z):

$$V_z = V_s/P, \tag{3}$$

where:

V_s – volume of the water that remains in the system recharging the intake for the last 38.2 days [m^3],

P – effective porosity [–].

Unfortunately, the obtained value will always be somewhat approximated due to the necessity to assume the medium effective porosity of the rocks through which the water saturated with radon flows towards the intake. This results from the heterogeneity of this parameter, especially with regard to groundwaters of shallow circulation. These waters flow through rocks weathered in varying degree, which additionally can be cut by tectonic faults, fissures, etc.

As for the groundwaters of Lądek Zdrój, the porosity of reservoir rocks equals 0.89%, and 7.1% for slightly weathered rocks [54]. According to other authors, the porosity of Gierałtów gneisses oscillates between 2.50–4.50% [16]. Particularly intensive dissolving of radon takes place in the outflow zone of deep circulation waters. Considering the comparable thickness of solid and weathered rocks, as well as the occurrence of fault and fissuring zones on the routes of water flow in this area, the adopted value of porosity equals 4%. In the case of Świeradów Zdrój and Kowary, the porosity values for unweathered crystalline rocks oscillate between 0.1 and 1%, and they can reach 6% for weathered rocks [16, 44, 45]. Therefore, in Świeradów Zdrój and Kowary, where the intakes are situated within weathered and fissured rocks cut by faults, and at the contact of weathered granite and an aplite vein respectively, the porosity value has been adopted at 4%.

When it comes to the intakes discharging a mixture of waters where only one component contains radon (or contains more radon than all the others), the proportions of the mixing waters must be considered in calculations. Therefore, the values of radon concentration in the radon-rich component will be higher than those measured in the intake. One can calculate them knowing the percentage of these waters in the mixture flowing out from the intake. It is possible to obtain such information by means of chemical (e.g. Ogilvi's) and/or isotope methods. Chemical methods are based on quantitative differences in the content of particular ions or the total of the dissolved solids in the mixture of two or more water components. The proportions of particular chemical ingredients in the mixture will vary depending on the amount of each component at a given moment. One can use this effect, provided that they know the chemical composition of at least one component. Isotope methods, on the other hand, instead of focusing on fluctuations of the chemical composition, make use of the quantitative differences in the isotope composition of water (stable isotopes of oxygen and hydrogen). Mixing of waters, precisely diluting mineralised waters of deep circulation by more shallow waters, can be observed in Górne intake in Świeradów Zdrój. The acidulous water admixture – the deep circulation component with minute content of radon – reaches the average value of ca. 15.5% in this intake [5, 8]. When calculating the volume of rocks supplying radon to this intake, one should take into consideration solely 84.5% of the water volume in the system (or of the discharge), as these are the only shallow circulation waters that are considerably saturated with radon.

Knowing the volume of rocks supplying radon to a groundwater intake, and realising that these waters circulate at small depths, it is possible to estimate the size of the area where the generated radon dissolves in groundwaters. Consequently, it is possible to define the areas that should be subject to specific protection because of their role in supplying groundwaters with a potential curative element.

RESULTS AND DISCUSSION

The medium content of radon, as a potential or actual curative element of selected groundwater intakes (including those regarded as medicinal), has been presented in Tab. 1. This table also includes other parameters necessary for calculating the volume of rocks supplying radon to a groundwater intake, and the results of these calculations.

The obtained results show that the volume of the rocks supplying radon to the groundwaters of particular intakes oscillates from over ten to several hundred thousand cubic meters. Radon dissolves particularly intensively in the outflow zones of these waters, mostly due to quite high degree of weathering changes [1, 10–12, 23, 27, 36–40]. Taking this into consideration, it is possible to estimate the size of the neighbouring area that supplies radon to the waters discharged by this intake. The proximity of the radon supply area to the intake of radon waters is also determined by the half-life of radon, which does not allow far migration of this gas [37–40]. Assuming that most radon-222 dissolves at the depths from 0 to ca. 50 m below the ground level, the size of the area supplying radon to groundwaters would oscillate from several hundred to several thousand square metres. In order to illustrate how small this area is, it is enough to compare it with the area of a circle with the radius from ca. 10 to 50 m or of a rectangular with the dimensions from ca. 10×30 m to ca. 70×100 m. As a rule the shape of this area is irregular, which is related to the routes of the groundwater flow to the intake. The area adjoins the intake on the side of the groundwater inflow, therefore the intake is not usually situated in the centre of the radon supply area, but in its marginal part.

The largest radon-222 supply areas are characteristic of the most discharge intakes. It results from the existence of highly permeable routes of water migration (with high effective porosity) close to the intakes. This enables transporting a large quantity of water, but also the release of a large amount of radon from the rocks, its easy dissolution and fast transport. Particularly the fast transport (high groundwater flow rate in open fissures and pores) enables radon-222 to reach the intake from quite large distances. Such a situation can be observed in Jerzy and Wojciech intakes in Lądek Zdrój, and in MCS intake in Świeradów Zdrój.

The smallest radon-222 supply areas are characteristic of groundwater intakes of low discharge (e.g. no. 26 in Kowary), in particular the intakes of groundwater mixtures, where only one component supplies substantial quantities of radon-222 (e.g. Górne in Świeradów Zdrój).

The estimated sizes of the areas supplying radon-222 to groundwater intakes imply that in view of safeguarding the reserves of this gas as a specific (curative) element, a relatively small area should be taken under protection. This area is generally larger than the immediate protective zone of a groundwater intake, which is subject to particular protection. Outside this area special protective regulations often operate with reference to so-called zones of health-resort protection. However, these zones incorporate solely the groundwater intakes currently used in balneology and, among the examined intakes, they do not include intake no. 26 in Kowary. Protection is also guaranteed to waters extracted in mining areas. Also in this case intake no. 26 in Kowary lies outside the protective zone, since no mining area has been created for these waters. Some intakes situated in national parks, nature reserves and other conservation areas are also taken under some protection. However, this form of protection refers only to intake no. 26 in Kowary.

The indicated recharge areas of the groundwaters in which radon is dissolved are generally quite remote from the intakes and are not identical with the areas supplying these intakes with radon-222. The groundwater recharge areas are also often situated outside any protective zones [6–8]. The indicated areas supplying intakes with radon are so small that in the scale of a map they are virtually identical with the symbols denoting these intakes (cf. Fig. 2–4).

When protection involves all the circulation systems of groundwaters containing radon-222, i.e. their recharge areas, flow zones and intake (outflow) zones, there is no need to create additional zones protecting radon-222 reserves. However, no complex protection of this kind is currently provided to groundwater deposits, including radon groundwaters. Therefore, it seems to be essential to extend slightly the existing intake protection zones, which would fully safeguard radon-222 reserves against disadvantageous influence of anthropogenic factors and some natural agents. It seems particularly important to ensure the preservation of the existing conditions of groundwater flow and radon migration in the intake areas. The most important element is the preservation of natural effective rock porosity in radon-222 supply areas.

CONCLUSIONS

The volume of the rocks supplying radon to the groundwaters of particular intakes oscillates from over ten to several hundred thousand cubic metres. Considering radon dissolution at the depth from 0 to ca. 50 m below the ground level, we obtain the total radon supply area of several hundred to several thousand square metres for a particular intake. This area usually has irregular shape related to the pathways of groundwater flow to the intake and it adjoins the intake on the side of the groundwater inflow.

The largest radon-222 supply areas are characteristic of the most discharge intakes. The smallest ones, on the other hand, are typical of groundwater intakes of small discharge, particularly the intakes of groundwater mixtures, where only one component supplies considerable amounts of radon-222.

The indicated recharge areas of radon-dissolving groundwaters are usually quite distant from the intakes and they are not identical with the areas supplying these intakes with radon-222.

Once the whole circulation systems of radon-222-rich groundwaters are taken under protection, there is no need to create additional protection areas in order to preserve radon-222 reserves. At the moment it seems to be important to extend slightly the existing zones of direct protection of the intakes, which could fully safeguard radon-222 reserves against disadvantageous influence of mainly anthropogenic factors. A particularly essential element is the preservation of natural effective rock porosity in the areas supplying intakes with radon.

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