Determination of the activity and the average annual dose of absorbed uranium and polonium in drinking water from Warsaw

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Abstract

Uranium and polonium isotopes were measured in tap water and groundwater from the Warsaw area (Poland). The mean values of ^{210}Po , ^{234}U and ^{238}U in surface intakes were 0.12, 3.91 and 2.75 mBq dm^{-3} and for deep water intakes were 0.25, 0.24 and 0.20 mBq dm^{-3} , respectively. The annual dose absorbed as a result of the consumption of drinking water by a inhabitant was calculated on the basis of measurements of polonium and uranium activity. The calculated value is only a negligible part (approximately 0.02%) of the dose taken from natural sources, which is estimated at 2.4 mSv year^{-1} .

Keywords Drinking water · Dose estimation · Oligocene sands · Uranium · Polonium-210 · Alpha spectrometry

Introduction

The occurrence of the radioactive isotopes ^{238}U , ^{234}U , ^{210}Po and their decay products in water is a natural phenomenon. Their concentration in groundwater depends on the quantity and seasonal diversity of precipitation, the infiltration time and the type of rocks through which the water flows etc. In some cases, the concentrations of these radioactive isotopes are elevated, and as a consequence, these isotopes may affect the lives and health of living organisms. Therefore, it is important to monitor concentrations of radionuclides in drinking water. The current drinking water legislations regulate the content of radioactive substances in water intended for human consumption to protect citizens against substances harmful to their health and lives. The recommended average global human exposure limit is 2.4 mSv year^{-1} [1, 2]. Meanwhile, the worldwide average annualized effective dose (mSv) absorbed by ingestion of food and drinking was calculated at 0.29 mSv year^{-1} [2, 3]. An example from one of the applicable regulations on the content of radionuclides in drinking water is the European Union Directive of 2013 [4]. According to this regulation, the indicative dose (ID) in water intended for human consumption should be no more than 100 $\mu\text{Sv year}^{-1}$ (except tritium, potassium ^{40}K ,

radon and radon decay products in relation to the volume of annual water consumption 730 dm^3 for adults). According to the Decree of the Polish Ministry of Health (2017), the same standards for drinking water quality are also applied in Poland [5].

Uranium isotopes remain in the natural environment for a very long time due to their half-lives (2.45×10^5 years for ^{234}U , and 4.47×10^9 years for ^{238}U) [6]. The ^{238}U isotope and the less frequent ^{234}U occur naturally in the (IV) oxidation state in minerals (e.g., monacites, kenenotimes, allanites), which are components of various types of rocks. As a result of the rocks weathering, the uranium oxidizes to the (VI) oxidation state [7] through which it can be dissolved in water [8]. A small fraction of the uranium isotopes come from the dust produced by rock weathering or coal-fired power plants, which are rich in these elements [9]. Occasionally, larger quantities of ^{234}U than ^{238}U are observed in water, and this phenomenon may be related to rock weathering [10, 11]. Uranium is harmful to animal [12] and human health [13] due to high radioactivity (alpha particle emission due to decay) and first of all its toxic chemical properties [14].

Studies of surface and groundwater carried out in various locations in Poland showed that the average activity concentrations of ^{238}U , ^{234}U and ^{235}U in tap waters from surface water were 9.6, 12.8 and 0.41 mBq dm^{-3} , respectively, and for treated water coming from deep water intakes were 4.5, 5.7 and 0.19 mBq dm^{-3} , respectively [15]. However, higher activities are also registered, e.g. in tap water in Katowice, where the concentration of ^{238}U

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ranged from 10.25 to 15.08 mBq dm⁻³ and ²³⁴U from 12.35 to 15.92 mBq dm⁻³ [16]. For comparison, the mean activity concentrations of ²³⁸U, ²³⁴U and ²¹⁰Po in drinking water samples in Italy were 21.4, 26.4 and 3.25 mBq dm⁻³, respectively [17].

As a result of successive ²³⁸U decays, ²²²Rn is formed, which, in the gaseous state, can move up the soil profile and accumulate in the lower parts of the atmosphere. In addition, ²²²Rn may be dissolved in water and then indirectly decay to ²¹⁰Po and finally to stable ²⁰⁶Pb. ²¹⁰Po in groundwater may come from the decay of parent isotopes adsorbed onto aquifer surfaces or dissolved within the water. Therefore, the activity of this isotope within surface water depends on the catchment geology, atmospheric precipitation of dust and anthropogenic sources [18].

The ²¹⁰Po isotope is a naturally occurring alpha particle emitter with a half-life of 138.38 days [6]. Due to its relatively short half-life, ²¹⁰Po is highly harmful to health when it is taken into the body by inhalation or ingestion [19]. Therefore, it is important to study the concentrations of this radionuclide in drinking water [20]. Polonium has four stable oxidation states, where the (IV) oxidation state is stable in solution under oxygen conditions. The occurrence of this isotope is related to biovolatilization, adsorption onto surfaces, precipitation in sulfides and incorporation into colloids [18].

The ²¹⁰Po isotope does not form independent phases in the environment because it has a relatively small natural abundance. In groundwater, the concentration of ²¹⁰Po is usually less than 40 mBq dm⁻³ [18], and in treated water, its activities are also low (the average value ranges from 3 to 5 mBq dm⁻³) [21]. The mean activity of ²¹⁰Po in drinking water in Poland is 0.5 mBq dm⁻³, while for the majority of countries, it does not exceed 4 mBq dm⁻³ [18]. However, sometimes the concentration of this radioisotope may be significantly higher, e.g., in groundwater wells across California, where its concentration varies in the range of 0.25–555 mBq dm⁻³ [22].

Previous studies in Poland have shown that ²¹⁰Po activity in water from the Vistula River is in the range of 1.94–3.21 mBq dm⁻³ [23], while ²¹⁰Po activity in water from the Oder River is 1.46–2.39 mBq dm⁻³ and from its tributaries is 1.02–3.64 mBq dm⁻³ [24]. In addition, similar measurements were also made for bottled mineral drinking water in Poland. The results showed that the mean concentrations of ²¹⁰Po, ²³⁸U and ²³⁴U in analyzed samples were 1.28, 0.80 and 0.80 mBq dm⁻³, respectively [25], while the mean activities of ²³⁸U, ²³⁴U, and ²¹⁰Po in drinking water in the Gdańsk agglomeration were 2.76, 2.86, and 0.48 mBq dm⁻³, respectively [26]. Generally, the activities of the studied radioisotopes are similar in Poland and other European countries. For example, the activity concentrations of ²³⁸U, ²³⁴U, and ²¹⁰Po in tap water samples from different locations

in Belgium were in the ranges of 0.3–16.8, 0.4–22.7, and 0.2–3.1 mBq dm⁻³, respectively [27].

In the present study, we evaluate the activity of ²³⁸U, ²³⁴U and ²¹⁰Po in drinking water of the Warsaw agglomeration (Poland) and try to characterize uranium and polonium activities in water from different sources. Based on these measurements, we calculated doses absorbed by the average citizen of Warsaw and compared them with norms and data from other cities. The research included observations of the variability of ²³⁸U, ²³⁴U and ²¹⁰Po concentrations in drinking water in Warsaw over time. These studies enabled a comparison of which isotopes are more abundant and the causes for these dependencies. Furthermore, the obtained results have made it possible to verify that the activity of radionuclides in water samples is not higher than the reference values described in the EU directive.

Materials and methods

Study area

Warsaw, the capital of Poland, is located in the east-central part of the country. The city population is officially estimated at 1,753,977 residents [28]. Warsaw is the largest city in Poland with an area of 517.2 km² and a calculated population density of 3306 people km⁻² [29].

The most important source of drinking water in Warsaw is tap water coming from surface and subsurface intakes. In the city, there are 5 zones supplying residents with drinking water. The drinking water for Warsaw is provided by the ‘Northern’ Waterworks Plant, ‘Warsaw Water Filters’ (Central Waterworks Plant), ‘Praga’, ‘Wawer’ and ‘Wesoła’ water treatment stations (WTSs). These waterworks plants meet the potable water demand in the city in 24%, 58%, 16%, 1% and 1%, respectively (personal communication).

The Vistula River covers over 70% of the agglomeration’s demand for water. Within the city, there are six riverside water intakes and the infiltration well, ‘Gruba Kaśka’, from which drinking water is taken. In addition, hydraulic chubbers, ‘Chudy Wojtek II’ and ‘Chudy Wojtek III’, are used to ensure proper aeration of the river bottom and a stable infiltration process. Other water sources are deeper intakes, which mainly take water from the ‘Oligocene’ aquifer. In the area of Warsaw, there are approximately 200 such intakes, half of which are in continuous use and are available to the residents of the capital. The ‘Wawer’ and ‘Wesoła’ WTSs also take water from deep water intakes.

The ‘Warsaw Water Filters’ WTS is the oldest and largest waterworks plant in Warsaw, which has supplied water to the inhabitants of Warsaw since the second half of the nineteenth century. The Central Waterworks Plant intakes water from the bottom of the Vistula River. It uses the natural

filtration process through a sand and gravel deposit, which forms at the bottom of the river. The uptake of water from the bottom of the river is done with 15 drains (perforated pipes spread radially around the well, at a depth of approximately 7 m), with a total length of nearly 2 km. The water filtered through the river bottom goes to the well, where it is pumped to the technological system. To treat raw water, aeration is used to remove iron and manganese compounds. The next process is coagulation and flocculation to remove the suspended particles. The water undergoes rapid filtration on sand-based filters, then ozonation and sorption on activated carbon. This stage allows the removal of organic compounds from water. The final process is periodic oxygenation of water, slow filtration on gravel—sand filters, and final disinfection with ClO_2 .

The ‘Praga’ WTS also intakes water from the bottom of the Vistula River. Similar to the ‘Warsaw Water Filters’, the ‘Praga’ WTS has a similar technological process for water treatment. In this case, however, this process is shorter and includes aeration, rapid filtration on sand-based filters, ozonation, sorption on activated carbon and disinfection with ClO_2 .

The ‘Northern’ Waterworks Plant in Wieliszew is the youngest of the waterworks plants in the area of Warsaw. The surface water is collected through a three-channel border water intake from Zegrzyńskie Lake, which is fed by the Bug and the Narew rivers. The technological process of water treatment involves the sedimentation of raw water in contact tanks, thanks to which heavier pollutants fall to the bottom. The water is then treated by coagulation (1st degree) and pressure flotation processes. Then, after ozonation, water undergoes coagulation (2nd stage) and sedimentation in pulsators, resulting in the suspended particles settling to clarify the water. Finally, rapid water filtration takes place on the gravel-sand filters, and then the water is disinfected using ClO_2 .

‘Oligocene’ water comes from the Mazovian basin, which is a shallow system with a size of over 50,000 km² (Fig. 1).

Fig. 1 Geological cross-section: 1: Quaternary; 2: Pliocene; 3: Miocene; 4: Oligocene; 5: Upper Cretaceous [30, modified]

The ‘Oligocene’ layer is 50 ± 100 m thick and is a major aquifer from the Tertiary period. The ‘Oligocene’ sandy aquifer is underlain by slightly permeable marine calcareous formations of the Upper Cretaceous and overlain by Miocene, Pliocene and Quaternary sediments [30]. Waters occurring in the ‘Oligocene’ formations are subartesian or artesian, depending on the geological structure. Exploited ‘Oligocene’ levels occur in the area of Warsaw at an average depth of 170–240 m. ‘Oligocene’ deposits are composed of fine and medium-grained sands with glauconite, which is characteristic of sediments formed in the shallow sea [31]. The age of water from ‘Oligocene’ deposits is estimated to be from the Late Glacial-Holocene period [30]. ‘Oligocene’ water, due to the iron and manganese compounds present in it, is treated in local water treatment stations situated in Warsaw and the surrounding areas.

Sampling procedure

Sixty samples of drinking water, every of volume 22.5 dm³, were collected in polyethylene tanks. Samples were coming from the waterworks plants located in the Wola district (2 sites) and Praga Południe district (1 site) and from deep wells (7 sites) located in the west part of Warsaw (Fig. 2). Two surface intakes and one deep well were monitored monthly over 1 year period and from other sites water was sampled only once. The nitric acid was added to each sample (to pH ~ 2) to avoid precipitation of uranium and polonium on tank walls [32]. Additionally, the mixture of isotopic tracers ($^{208}\text{Po} + ^{209}\text{Po} + ^{236}\text{U}$) which enabled control of the chemical recovery of selected elements, was added at the same

Fig. 2 Map of study area with the sampling locations

time. The activity of ^{208}Po , ^{209}Po and ^{236}U added to every sample was approximately 25, 8.5 and 38 mBq, respectively.

Alpha source preparation

Polonium and uranium extractions from the samples were carried out according to the procedure of sequential separation, which is a modification of the method proposed by Benedik et al. [33]. Polonium and uranium were co-precipitated with iron (III) oxide-hydroxide using 2–5 cm³ of iron chloride and appropriate amount of ammonia to obtain pH 7–8 [34]. The supernatant was removed by decanting and the residue was centrifuged (4000 rpm, for 10 min) to completely separate the precipitate. Then, the precipitate was dissolved in 20 cm³ concentrated HCl and converted three times to 20 cm³ concentrated HNO₃. Each of these steps was ended by centrifuging the sample (4000 rpm, for 5 min) and decanting solution. Finally, the obtained solution was evaporated to dryness, and then a small amount of H₂O₂ was added to eliminate the organic matter from the sample. The residue was dissolved in 100 cm³ 0.5 M HCl and transferred into PTFE vial. Ascorbic acid and hydroxylamine hydrochloride to reduce Fe(III) to Fe(II) form [35].

Then, polonium was spontaneously electrodeposited [36] from the solution on silver discs (diameter 25.2 mm) with using a magnetic stirrer (temperature 80 °C, 500 rpm) for 3 h. The typical chemical recovery for polonium was 40–60%. After that, the disks were carefully cleaned with deionized water and measured for polonium activity.

Uranium was separated from the solution remaining after polonium deposition with chromatographic columns [37]. The solution was evaporated to dryness and residue was dissolved in 50 mL of 9 M HCl. Then, it passed through the ion exchangeable resin Dowex 1X8 (50–100 mesh, Cl-form) conditioned by 50 mL 9 M HCl. The uranium remaining on the resin was eluted with 25 mL of 8 M HNO₃ and with 50 mL deionized water, and the total collected solution was evaporated. After evaporation the solid residue containing uranium was dissolved in 0.75 M (NH₄)₂SO₄ solution and then it was transferred to an electrolytic cell. The typical chemical recovery for polonium was 40–60%. Finally, uranium isotopes were electrodeposited on stainless steel discs (diameter 25.2 mm) at a current density of 1.2 A cm⁻² for 3 h.

Radionuclide measurements

The activities of polonium (^{210}Po) and uranium (^{238}U , and ^{234}U) isotopes were measured using the Octete (Ortec) alpha particle spectrometer with silicon detectors (active area 1200 mm²) at the Uranium Series Laboratory at the Institute of Geological Sciences PAS in Warsaw. Lower detection limit for a 22.5 dm⁻³ sample and 600,000 s

counting time was 0.02 mBq dm⁻³ for uranium isotopes and 0.07 mBq dm⁻³ for polonium. The Maestro-32 software was used for data acquisition. The uncertainty of results (combined uncertainty) was calculated using uncertainty propagation rules. Typical uncertainty budget for tap water sample was reported in Table 1.

The results of measurements were expressed as mBq per dm³. Similarity in activity values between study groups of sites was tested with ANalysis Of SIMilarity (ANOSIM) method [38]. The annual dose absorbed by the consumer was calculated assuming that the average amounts of annual water consumption are 250, 350, and 730 dm³ year⁻¹ for infants, children and adults, respectively. The activity conversion factors per absorptive dose are 4.5×10^{-8} , 4.9×10^{-8} , and 1.2×10^{-6} Sv Bq⁻¹ for ^{238}U , ^{234}U and ^{210}Po , respectively [2].

Results

The measured concentrations of radionuclides in water samples are in the ranges of < 0.02–7.32, 0.04–9.41, and < 0.07–0.68 mBq dm⁻³ for ^{238}U , ^{234}U and ^{210}Po , respectively. The measured activities of U and Po radionuclides were relatively low, but they differed in the particular source of water. The mean activities of ^{238}U , ^{234}U and ^{210}Po in the tap water collected from the Wola district are 2.29 ± 0.08 , 3.03 ± 0.09 , and 0.12 ± 0.05 mBq dm⁻³; from the Praga Południe district are 3.22 ± 0.10 , 4.78 ± 0.12 , and 0.13 ± 0.03 mBq dm⁻³; and in the treated groundwater collected from deep wells are 0.20 ± 0.02 , 0.24 ± 0.02 and 0.25 ± 0.03 mBq dm⁻³, respectively (Fig. 3). The mean specific activity of ^{234}U was higher than ^{238}U in the tap water as well as in the deep-well waters (Fig. 3). The difference in concentrations of uranium isotopes in the treated surface water samples is over 1 mBq dm⁻³, while in waters from the ‘Oligocene’ aquifer specific activity of both isotopes is similar.

In addition, the concentrations of these two radionuclides are much higher in tap water than in groundwater (Fig. 3). Generally, uranium isotopic composition of surface water is

Table 1 Typical uncertainty budget for a single measurement of tap water sample from Praga district

Uncertainty budget	^{238}U (%)	^{210}Po (%)
Tracer counting (incl. back.)	3.8	3.2
Counting ^{238}U or ^{210}Po (incl. back.)	4.0	3.3
Weighing of tracer	0.2	0.1
Activity of tracer	6.5	6.5
Volume of sample	0.8	0.8
Combined uncertainty	8.6	8.0

Fig. 3 The mean activity of ^{238}U , ^{234}U and ^{210}Po (mBq dm^{-3}) in drinking water collected from deep wells and the Praga and Wola districts. Uncertainty is given as combined uncertainty

not different in both (Wola and Praga) Warsaw districts (ANO-SIM $p > 0.05$). On the other hand, both surface intakes differ significantly from groundwater (ANOSIM $p = 0.01$, and $p = 0.007$, respectively).

Oppositely, the activity of ^{210}Po in drinking water from deep water intakes is higher than from the surface intakes (Fig. 3). Thus, the average activity of ^{210}Po in groundwater (0.25 mBq dm^{-3}) is almost two times higher than in the tap water from the Praga and Wola districts (0.12 mBq dm^{-3}). In addition, the highest ^{210}Po activity was measured in samples from deep water intakes located in the Wola district (Fig. 2).

The activity of the uranium isotopes is highly correlated in surface and groundwater (Fig. 4). Uranium and polonium isotopes show a low negative correlation in surface water and no correlation in deep well water.

The mean concentrations of isotopes (the total activity of ^{238}U , ^{234}U , ^{210}Po) in drinking water samples from deep wells, the Praga and Wola districts, as well as the annual intake and effective dose calculated per person (depending on age), are presented in Tables 2 and 3.

The amount of the annual intake per Warsaw inhabitant is the highest for adults (5.93 Bq) who are consuming tap water from the Praga district (Table 2). Furthermore, the calculated value for consumers from the Wola district (3.97 Bq) is also high. The lowest annual intake per person is observed for consumers whose are drinking groundwater from the ‘Oligocene’ aquifer. On the other hand, the calculated effective dose is high for adults who consume treated water from deep wells ($0.24 \mu\text{Sv year}^{-1}$), which is due to the higher concentration of ^{210}Po in groundwater than in surface water (Table 3).

Discussion and conclusions

The most prominent observation on obtained data set is different isotopic signature of water coming from different sources. Uranium activities were the lowest in deep well

Fig. 4 The correlation of isotope activity in drinking water samples collected from the Praga and Wola districts and deep wells from ‘Oligocene’ aquifer. **a** ^{234}U to ^{238}U ratio; **b** ^{238}U to ^{210}Po ratio; **c** ^{234}U to ^{210}Po ratio (mBq dm^{-3})

Table 2 The mean concentrations of ^{238}U , ^{234}U and ^{210}Po for drinking water collected from the Praga, Wola districts and deep wells

	Mean concentration (mBq dm^{-3})		
	Praga	Wola	Deep wells
^{238}U	3.2	2.29	0.20
^{234}U	4.8	3.03	0.24
^{210}Po	0.13	0.12	0.25
Total	8.13	5.43	0.70

Table 3 Summary of the annual intake per person and effective dose for different age groups from combined ^{238}U , ^{234}U and ^{210}Po measured in drinking water samples from the Praga, Wola districts and deep wells

	Annual intake per person (Bq)			Effective dose ($\mu\text{Sv year}^{-1}$)		
	Adults	Infants	Children	Adults	Infants	Children
Praga	5.93	2.03	2.84	0.39	0.13	0.19
Wola	3.97	1.36	1.90	0.29	0.10	0.14
Deep wells	0.51	0.18	0.25	0.24	0.08	0.11

water. The low activity of U could be a result of the mineralogical composition of the rocks forming the aquifer. A high content of glauconite in ‘Oligocene’ sands increases the sands sorption capacity [39]. As a result, water is filtered as it goes through sand layers and U content is significantly ($p < 0.01$) lower in groundwater than in meteoric water (Fig. 3). Activity of ^{238}U and ^{234}U in groundwater in Poland varies over a relatively long range; the lowest activities were measured in Ostrołęka in Central Poland (0.4 ± 0.1 and 0.5 ± 0.1 mBq dm^{-3} , respectively), while in Suwałki (Northern Poland), activities were as high as 23.2 ± 1.6 and 25.7 ± 1.7 mBq dm^{-3} , respectively [15]. The differences are caused by the geological properties of aquifer rocks: low uranium concentrations are related to fluvioglacial sands and high uranium concentrations are related to crystalline rocks and glacial till with crystalline rock debris. As the ‘Oligocene’ aquifer is composed primarily of sands with glauconite, our measurements are even lower than values reported for other localities in Central Poland [15]. In surface intakes, U activity was higher by an order of magnitude and was the highest in the Praga district intakes (Fig. 3). The difference in uranium activity between the Praga and Wola districts is caused by slightly different processes at the treatment stations. Although the source of water is similar for both water stations, the filtration process is much longer at the ‘Warsaw Water Filters’ WTS supplying the Wola district. Consequently, some amount of uranium is stopped in the slow sand filter biofilm. It is confirmed with lower activity of treated water (this study) comparing to untreated water from Vistula river [15] and the difference is ~ 1 mBq dm^{-3} for Praga and ~ 2 mBq dm^{-3} for Wola district. The surface water in our study has a uranium isotope characteristic similar to that previously measured in Warsaw and to tap water in the Płock and Gdańsk agglomeration [15,

26]—both cities also take water from the Vistula River. In other Polish rivers, especially those with higher amounts of crystalline rocks in their catchments (e.g., in Sudety Mts. Region), ^{238}U and ^{234}U activity can be as high as 23.9 ± 2.7 and 34.1 ± 3.9 mBq dm^{-3} , respectively [15].

There is no such clear differences between surface intakes and deep wells in terms of polonium activity. Anyway, it demonstrated an opposite relationship to uranium and has a slightly higher concentration in groundwater (Fig. 3). The elevated activity of Po in deep wells can be a result of relatively high concentrations of radon in groundwater, a parent isotope for ^{210}Po [40]. Radon, an isotope of the uranium decay chain, may originate in aquifers from uranium isotopes contained in ‘Oligocene’ sands. However, even the relatively elevated activity in groundwater from the Warsaw basin is still lower than the activity in surface water in northern Poland [26]. Water from the surface intakes also has activity below values recorded for other sites in the Vistula River catchment area [23].

Results obtained for Warsaw region, both from deep wells and surface intakes, are relatively low comparing to other European localities (Table 4) and are similar to values for bottled mineral water in Croatia. They are also much lower than the derived concentrations for radioactivity for ^{238}U , ^{234}U and ^{210}Po of 3.0, 2.8 and 0.1 Bq dm^{-3} , respectively, in water intended for human consumption [4].

The annual intake of uranium calculated for surface intakes in Warsaw (Tables 2, 3) was similar to value from Gdańsk [26], but the polonium intake was only half of the previously reported amount. Consequently, the calculated effective dose from all sources (Table 3), is also half of that in the Gdańsk agglomeration.

The annual absorbed dose taken from the examined water is only a negligible part (approximately 0.02%) of the dose

Table 4 The activity concentration ranges of uranium isotopes and polonium (in mBq dm^{-3}) in tap and bottled water in selected locations in Europe and Australia

Sample	Location	^{238}U	^{234}U	^{210}Po	Refs.
Bottled water	Belgium	0.3–26.1	0.3–54.4	0.2–3.1	[27]
Tap water	Belgium	0.3–16.8	0.4–22.7	0.2–3.1	[27]
Tap water	Italy	0.206–103	0.249–135	0.13–11.3	[17]
Tap water	Australia	0–14.3	0–12.8	0–114.2	[41]
Bottled spring water	Croatia	3.4–14.6	4.7–36.5	0.51–3.0	[42]
Bottled mineral water	Croatia	2.1–10.7	6.4–15.3	0.25–0.7	[42]
Tap water	Poland (Warsaw)	<0.02–7.32	0.04–9.41	<0.07–0.68	This study

taken from all sources, the value of which is estimated at 2.4 mSv year⁻¹ [2, 3]. This research shows that the dose from drinking water consumption in Warsaw is significantly lower than the indicative dose (ID) in water intended for human consumption (100 µSv year⁻¹) described by the EU directive.

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