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Research paper

Regional variations in water physicochemical properties and residual chlorine concentrations and incidence of cancer in Serbia

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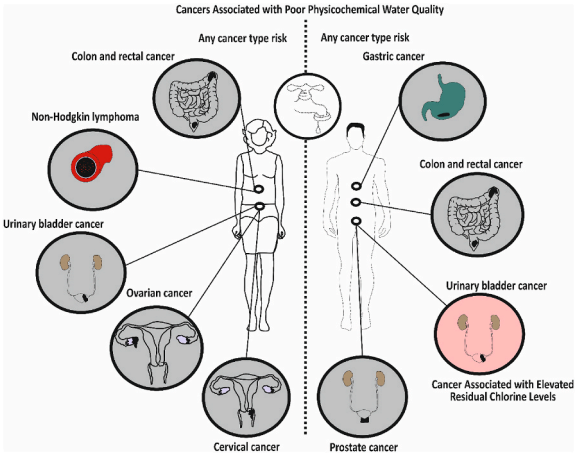
HIGHLIGHTS

- Poor water quality was associated with increased incidence of any type of cancer.
- Positive association was found for colon and rectal cancer in both males and females.
- Females showed positive association with ovarian cancer.
- High residual chlorine levels were positively associated with bladder cancer in males.

GRAPHICAL ABSTRACT



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ABSTRACT

Individuals are exposed to local water sources through routine activities in their place of residence. Serbia consists of 26 districts with a population of approximately 6.8 million inhabitants. Individuals in different districts are exposed to varying physicochemical water quality. Irregularities in physicochemical water properties may be linked to malignant diseases. This study aimed to investigate the association between the percentage of water which does not meet the standards for both physicochemical properties and residual chlorine, and standardized incidence of most common malignancies in Serbia. In 2013, 18.9 % of 76,758 water samples in Serbia were non-compliant (0 % in Kolubara, 97.4 % in Middle Banat), and in 2021, 16.5 % of 93,144 samples failed standards (0.9 % in Macva, 97.8 % in North Banat). A significant positive correlation was observed between the percentage of unsatisfactory physicochemical water samples from public water supply systems and water

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facilities and the standardized incidence of colon and rectal cancer in males and females, any cancer type in both sexes, and ovarian cancer in females. However, no significant correlation was observed for leukemia and pancreatic in males, brain tumors or lung cancer in both sexes. Bladder cancer in males was associated with exposure to residual chlorine which surpass recommended concentrations. Study findings suggest that exposure to water that does not meet adequate physicochemical standards may be associated with an increased risk of various cancer types, while residual chlorine above recommended standards seems associated with increased incidence of bladder cancer.

1. Introduction

Tap water is a source of environmental toxins when it does not meet the recommended values for physicochemical parameters (Li and Wu, 2019). In Europe, water quality standards are primarily governed by the EU Water Framework Directive, which sets strict regulations for surface and groundwater protection, monitoring, and pollution prevention (Carvalho et al., 2019; Rowbottom et al., 2022). Serbia, as an European Union (EU) candidate country, aligns its water legislation with these directives through the Law on Waters, which regulates water management, pollution control, and sustainable use of water resources.

Variations in quality of ground and surface water are driven by a combination of naturally occurring soluble salts and human-induced pollutants. In certain global regions, seasonal variations may also affect physicochemical properties of the groundwater (Aralu et al., 2024; Pande et al., 2025; Singh et al., 2023; Tanwar et al., 2024). Nonetheless, pollution from anthropogenic sources demonstrated a large impact on water quality and consequently on human health (Egbueri et al., 2025a; Egbueri, 2023; Yassin et al., 2024). These pollutants originate from both localized point sources, such as industrial and urban effluents (Karmakar et al., 2023; Najafi Saleh et al., 2020) and diffuse sources, primarily agricultural activities. In particular, agricultural activities have been shown to contribute to elevated nitrate (NO_3^-) and heavy metal concentrations in groundwater (Abu et al., 2025; Bouselsal et al., 2025; Egbueri et al., 2025b). In the EU, the use of pesticides and nitrogen in agriculture has deteriorated the quality of drinking water (Wuijts et al., 2021). Also in Serbia, water pollution can result from various anthropogenic activities (Devic et al., 2014, 2016; Veskovic et al., 2024). Elevated fluoride levels have been detected in groundwater in suburban areas of Belgrade (Antonijevic et al., 2016). Similarly, assessment of water quality in the river network of Serbia showed high contamination for total phosphorus, nickel (Ni), manganese (Mn), lead (Pb), arsenic (As), and mercury (Hg) probably explained by a set of multiple pollution sources including urban and agricultural runoff, lack of adequate treatment of wastewater from mining and industrial areas (Devic et al., 2016).

In 2013, in Serbia, 18.9 % of 76,758 examined water samples, from public water supply systems and water facilities did not comply with national standards (Knežević, 2014). Similar values were noted in the following years, with stable percentage of water samples not meeting physicochemical standards between 16.5 % and 20.7 % (Knežević, 2018, 2022). Several substances have been identified as exceeding recommended levels, including ammonia, iron, Mn, nitrites, As, and potassium permanganate ($KMnO_4$) (Jovanovic et al., 2011; Knežević, 2014).

In addition to chemicals, microbial alterations have been reported in the period 2013–2021 (Knežević, 2018). Chlorination is the main method to improve microbial properties of drinking water, especially in Europe (Evlampidou et al., 2020). However, when ammonia from microbial contamination is present in the water, chlorine forms some well-known disinfection by-products such as trihalomethanes, monochloramine, dichloramine, and nitrogen trichloride (Fantuzzi et al., 2007; Garcia-Villanova et al., 2010). In addition, chlorine forms some residuals, including hypochlorous acid (HOCl) and hypochlorite (OCl^-). Total residual chlorine consists of residual forms (HOCl and OCl^-) and available chlorine. Maximal tolerant concentration of residual chlorine by WHO and Serbia standards is 0.5 mg/L (WHO, 2022). When residual chlorine is present in higher concentrations above the recommended regulatory limits, disinfection by-products form to a greater extent, posing potential health risks (Deiana et al., 2025; Jauniaux et al., 2024; Mazhar et al., 2020; Righi et al., 2012), including cancer (Helte et al., 2025), especially colorectal and bladder cancer (Beane Freeman et al., 2017; Evlampidou et al., 2020; Helte et al., 2023; Villanueva et al., 2017, 2023).

Despite some previous studies conducted in Serbia evaluated specific district-level correlations for some contaminants with focused on selected chronic non-communicable diseases and cancer types (Jovanovic et al., 2011; Jovanovic et al., 2013; Jovanovic et al., 2012; Rajovic et al., 2024; van den Berg et al., 2023), none of previous investigations, to the best of our knowledge, examined the overall physicochemical properties of drinking water in relation to cancer incidence in Serbia. Therefore, the aim of this study was to examine the association between water quality and cancer incidence across 25 districts of Serbia by performing correlation analysis. Specifically, we analyzed the relationship between (1) the percentage of water samples that did not meet physicochemical standards, (2) the percentage of samples exceeding the recommended levels for residual chlorine, along with the average of the maximally measured concentrations of residual chlorine in public water supply systems and water facilities, and (3) the standardized incidence rates of the most common malignancies in adult population. The analysis was conducted for two time points—2013 and 2021—across all administrative districts.

2. Methods

2.1. Study setting and data collection

The Republic of Serbia is divided into 26 districts: North Bačka, Middle Banat, North Banat, South Banat, West Bačka, South Bačka, Srem, the City of Belgrade, Mačva, Kolubara, Danube, Braničevo, Šumadija, Morava, Bor, Zaječar, Zlatibor, Moravica, Raška, Rasina, Nišava, Toplica, Pirot, Jablanica, and Pčinj (Fig. 1), with a total population of 6,647,003 inhabitants in 2022.

The Institute of Public Health of Serbia "Dr. Milan Jovanović Batut" collects district-level data and publishes annual public health reports for all regions of Serbia, except for Kosovo and Metohija, due to the unavailability of data. Among these reports, analyses of drinking water safety from public water supply systems in various settlements are collected, including both urban and rural areas, and organized by region (Knežević, 2014; Knežević, 2018, 2022).

These annual water quality reports provide detailed information, including the percentage of water samples that met or failed to meet national standards for physicochemical and microbiological parameters, as well as the number and percentage of monitored public water supply systems per each Serbian district. Each report specifies the exact number of water samples tested and the number of those that did not comply with standards for either physicochemical or microbiological properties.

In addition to water quality data, the Institute also publishes annual reports on the standardized incidence rates of the ten most common cancer malignancies, as well as other major non-communicable diseases such as diabetes mellitus and coronary syndrome (Jovanovic et al., 2011, 2012).

Water quality data were retrieved for the purposes of this study from annual water quality reports published in 2014 and 2022, specifically focusing on the percentage of physicochemically unsatisfactory water samples from public water supply systems and water facilities in each district (Bijelovic et al., 2022; Knežević, 2014, 2022). More precisely, as for the physicochemical water quality assessment, data from two years nearly a decade apart was used, namely 2013 and 2021 and calculated percentage of water samples not meeting physicochemical standards in 2013 and 2021 (Table 1 and Fig. 1). Two temporally distant reports were selected, as exposure to environmental factors and the potential development of malignancies typically require a long latency period. Similarly, based on annual reports from 2017 to 2022, the average percentage of water samples not meeting residual chlorine standards was calculated by the authors, as well as the average of the maximum residual chlorine levels recorded during that period (Table 1 and Fig. 1).

Data of age-standardized incidence of malignancies in adult population was obtained per each district in 2022 from the same Institute of Public Health of Serbia (Miljus and Zivkovic Perisic, 2024). Cancer types analyzed included the ten most common cancers in males and females: overall cancer incidence (C00-C97), colon and rectum cancer (C18-C20), pancreatic cancer (C25), lung cancer (C34), and bladder cancer (C67), and brain cancer (C71). In males, additional outcomes were oral (including pharyngeal) cancer (C00-C10), gastric cancer (C16), laryngeal cancer (C32), prostate cancer (C61), and overall leukemia in males (C91-C95), while in females they were breast cancer (C50), cervical cancer (C53), uterine cancer (C54), ovarian cancer (C56), and non-Hodgkin lymphoma (C82-C85).

This study is secondary data evaluation using anonymous and aggregated data, therefore, ethical approval was waived.

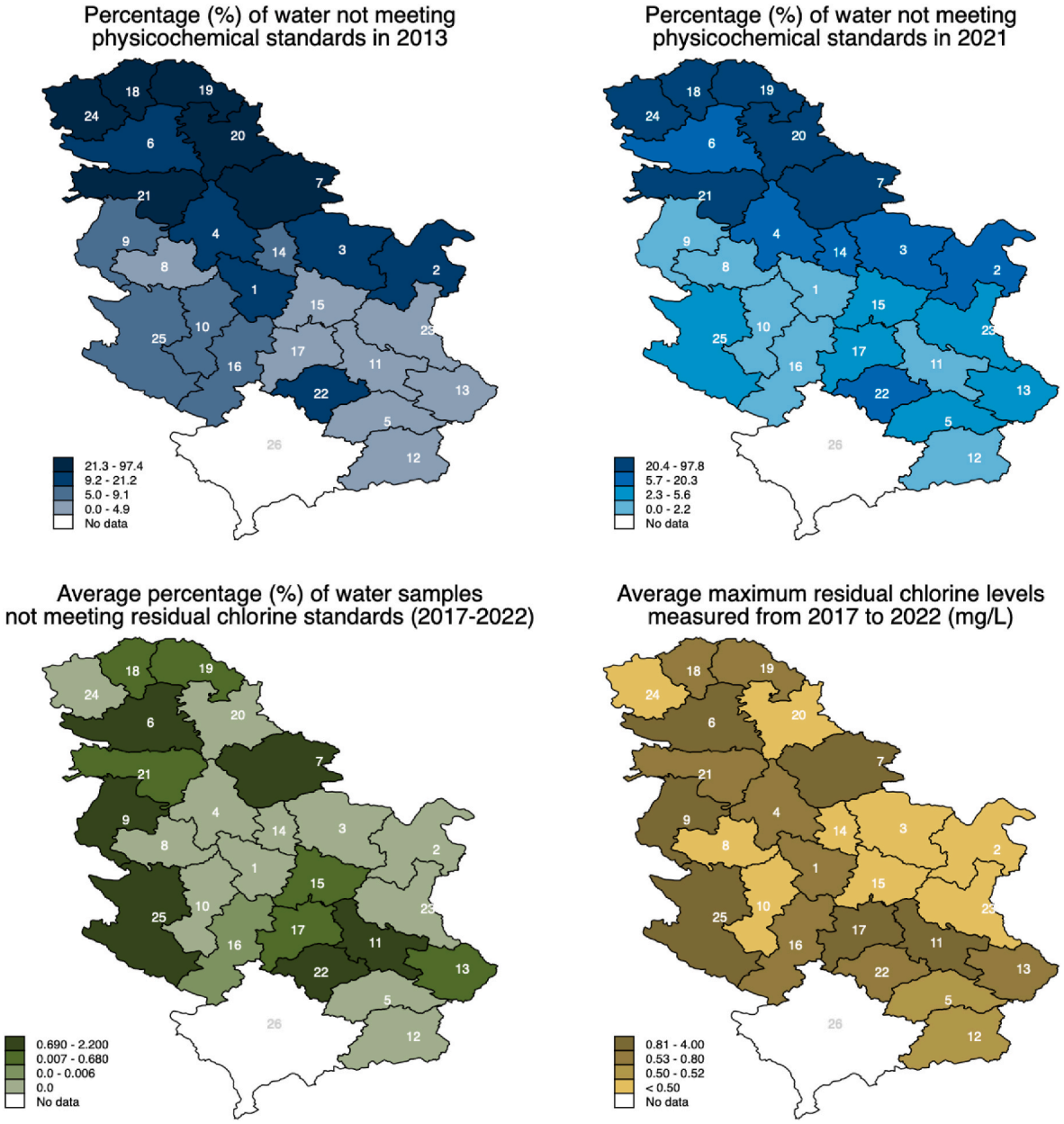

Fig. 1. Thematic maps visualizing water quality parameters across administrative districts of the Republic of Serbia: 1. Sumadija; 2. Bor; 3. Braničevo; 4. Belgrade; 5. Jablanica; 6. South Bačka; 7. South Banat; 8. Kolubara; 9. Mačva; 10. Moravica; 11. Niš; 12. Pcinj; 13. Pirot; 14. Danube; 15. Morava; 16. Raška; 17. Rasina; 18. North Bačka; 19. North Banat; 20. Middle Banat; 21. Srem; 22. Toplica; 23. Zaječar; 24. West Bačka; 25. Zlatibor; 26. Kosovo and Metochia (no data).

Table 1
Data on the percentage of water samples not meeting physicochemical standards for the years 2013 and 2021 and data on residual chlorine for the years 2017–2022.

District	Percentage (%) of water not meeting physicochemical standards in 2013	Percentage (%) of water not meeting physicochemical standards in 2021	Average percentage (%) of water samples not meeting residual chlorine standards from 2017 to 2022	Average maximum residual chlorine levels measured from 2017 to 2022 (mg/L)
West Bačka	34.7	41.0	0.0	<0.5
North Bačka	55.0	32.8	0.28	0.664
North Banat	80.5	97.8	0.06	0.55
South Bačka	16.3	20.3	1.26	4.0
Middle Banat	97.4	97.1	0.0	<0.5
South Banat	57.9	44.2	2.08	1.74
Srem	52.0	34.5	0.04	0.52
Mačva	7.0	0.9	1.0	1.28
Belgrade	11.1	8.5	0.0	0.6
Kolubara	0.0	1.7	0.0	<0.5
Danube	9.1	7.4	0.0	<0.5
Braničevo	21.2	6.0	0.0	<0.5
Bor	13.3	13.9	0.0	<0.5
Zlatibor	5.2	2.8	0.76	0.82
Morava	4.9	5.6	0.02	<0.5
Sumadija	19.3	1.1	0.0	0.54
Moravica	5.1	1.4	0.0	<0.5
Zaječar	4.9	5.5	0.0	<0.5
Raška	5.2	1.1	0.006	0.52
Rasina	3.2	3.4	0.68	1.28
Toplica	17.4	10.0	2.22	0.78
Pirot	3.7	3.7	0.06	0.8
Jablanica	0.9	2.3	0.0	0.5
Pcinj	3.8	2.2	0.0	0.5
Niš	1.3	1.7	0.8	0.84

2.2. Data analysis

The Kolmogorov-Smirnov test was used to check whether the data follows a normal distribution. Since the water quality data did not follow a normal distribution, Spearman correlation test was used to assess the relation between the percentage of unsatisfactory water samples from public water supply systems and water facilities across districts and the age-standardized incidence of malignancies. Statistical analyses were performed in easy R (EZR) version 1.68. Furthermore, geospatial and statistical data were integrated to visualize the percentage of water not meeting national criteria and residual chlorine levels. Thematic mapping was conducted using the '*grmap*' package in STATA software (version 18.0, StataCorp, College Station, TX, 2024).

3. Results

3.1. Water quality data for the years 2013; 2021

In 2013, the percentage of unsatisfactory water samples varied across districts, with the lowest reported in the Kolubara district, where all examined water samples met the recommended levels. In contrast, some districts in Vojvodina, such as Middle Banat, had 97.4 % of samples failing to meet the standards. For the entire country in 2013, 18.9 % of a total of 76,758 samples did not meet physicochemical standards, while in 2021, 16.5 % of 93,144 samples did not meet some of the physicochemical standards. In 2021, Macva district had the lowest rate of water with poor physicochemical properties (0.9 %), while in North Banat, this rate was 97.8 % (Table 1).

3.2. Data on the incidence of leading cancer types in Serbia in 2022

Lung cancer was the most common type of cancer in males, with a standardized incidence of 139.4 new cases per 100,000 inhabitants for the entire country (Table 2). For females, breast cancer was the leading type, with a standardized incidence of 131.4 new cases per 100,000 inhabitants in 2022 (Table 3). In both males and females, North Banat had the highest standardized incidence of all cancer types, with 928.3 and 997 new cases per 100,000 individuals, respectively.

3.3. Correlational analysis

In the correlation analysis between percentage of unsatisfactory water physicochemical properties in 2013 and standardized cancer incidence in 2022, we found a strong positive correlation with any cancer type in both males ($r = 0.515$, $p = 0.008$) and females ($r = 0.678$, $p < 0.001$) (Tables 4–5). We also found positive correlations in males with colon and rectal cancer ($r = 0.434$, $p = 0.030$), prostate cancer ($r = 0.438$, $p = 0.028$) and gastric cancer ($r = 0.395$ $p = 0.051$) (Table 4). In females, positive correlations can be noted with non-Hodgkin lymphoma ($r = 0.431$, $p = 0.031$), bladder cancer ($r = 0.400$; $p = 0.047$), and ovarian cancer ($r = 0.533$; $p = 0.006$), while other gynecological malignancies showed no correlations, with the marginal exception of weak and imprecise correlation with cervical cancer ($r = 0.307$, $p = 0.135$) (Table 5).

In the correlation analysis between percentage of unsatisfactory water physicochemical properties in 2021 and standardized cancer incidence in 2022, we found a strong positive correlation with any cancer type in both males ($r = 0.578$, $p = 0.002$) and females ($r = 0.755$, $p < 0.001$) (Tables 4–5). In males, strong positive correlation can be noted for colon and rectal cancer ($r = 0.526$, $p = 0.007$), while the correlations are weaker for gastric ($r = 0.350$, $p = 0.086$) and prostate ($r = 0.280$, $p = 0.174$) cancer (Table 4). In females, we found strong correlations with colon and rectal ($r = 0.578$, $p = 0.002$), pancreatic ($r = 0.406$, $p = 0.0443$) and lung ($r = 0.497$, $p = 0.012$) cancers, while weaker correlation with non-Hodgkin lymphoma ($r = 0.391$, $p = 0.053$). As regards gynecological cancers, we found positive correlation with both cervical ($r = 0.426$, $p = 0.033$) and ovarian ($r = 0.415$, $p = 0.039$) cancers (Table 5).

As regards correlation analysis between water samples not meeting residual chlorine standards, we found strong positive correlation with bladder cancer in males only ($r = 0.406$, $p = 0.043$) (Table 4), while no correlations emerged for females (Table 5). Conversely, the analysis between the highest residual chlorine concentrations and cancer incidence showed only marginal and weak correlations with lung and bladder cancer in males (Table 4), but strong positive correlation with uterine cancer in females (Table 5).

4. Discussion

4.1. Cancer as a global health issue: environmental factors as significant contributors

There are 20 million new cancer cases worldwide annually, reflecting its pandemic proportions. In most countries, lung cancer is the most common type, followed by breast cancer in females, as well as colorectal, prostate, and stomach cancers (Bray et al., 2024). Moreover, lung cancer ranks as the leading cause of cancer-related mortality. Some risk factors, such as age and sex, cannot be modified. However, environmental factors, such as exposure to heavy metals and metalloids can affect risk of cancer (Alimam and Auvinen, 2025; Cirovic and Cirovic, 2022; Cirovic and Satarug, 2024; Vinceti et al., 2018). When

Table 2
Data on standardized incidence of most common malignancies in males for the year 2022 in Serbia.

District	All cancers (C00-C97)	Oral and pharyngeal cancer (C00-C10)	Gastric cancer (C16)	Colon and rectal cancer (C18-C20)	Pancreatic cancer (C25)	Laryngeal cancer (C32)	Lung cancer (C34)	Prostate cancer (C61)	Bladder cancer (C67)	Brain tumor (C71)	Overall, leukemia (C91-C95)
West Bačka	846.6	28.2	17.0	143.0	26.2	17.0	174.4	99.3	55.5	21.7	19.4
North Bačka	901.2	19.3	38.9	212.5	33.7	10.2	174.5	106.6	77.0	24.6	19.3
North Banat	928.3	38.2	48.8	144.3	37.8	17.8	220.6	80.0	54.5	16.8	17.1
South Bačka	755.8	16.4	19.0	110.9	20.6	16.6	137.1	67.8	61.7	13.3	19.1
Middle Banat	928.3	20.0	27.0	162.5	25.9	12.1	115.1	105.1	55.0	11.2	11.2
South Banat	649.6	9.4	23.4	81.0	20.8	16.8	134.8	53.5	39.2	12.6	12.4
Srem	763.4	10.1	22.3	135.1	24.7	20.9	148.3	76.8	67.7	17.0	22.6
Mačva	640.4	12.3	18.9	68.8	18.3	9.3	137.2	59.1	63.5	17.0	10.9
Belgrade	689.2	21.3	27.1	60.9	29.7	15.3	173.7	87.9	39.9	15.1	13.6
Kolubara	640.9	8.4	23.3	87.0	24.1	11.8	141.5	75.4	24.3	17.8	15.0
Danube	614.3	14.0	21.7	91.0	19.1	28.7	126.1	71.3	46.3	18.0	21.5
Braničevo	573.7	18.0	21.3	98.7	20.1	29.2	106.3	47.7	55.2	7.6	16.6
Bor	717.5	19.9	36.3	93.4	17.0	26.6	112.3	88.9	50.8	21.1	21.5
Zlatibor	636.5	13.7	19.2	99.2	16.7	25.9	79.9	87.5	50.3	17.6	24.4
Morava	643.2	14.9	22.6	94.5	22.0	22.1	115.9	48.0	58.4	20.1	18.1
Sumadija	781.9	20.1	32.5	118.4	27.9	31.6	123.4	84.0	57.5	16.8	19.8
Moravica	613.3	17.2	19.0	76.4	21.6	8.2	126.0	161.9	51.6	8.2	12.6
Zaječar	598.3	13.5	13.5	98.7	17.5	24.1	99.9	59.2	42.9	11.7	16.8
Raška	582.9	6.1	18.9	83.0	20.3	14.6	131.2	71.5	39.5	15.8	13.4
Rasina	729.6	20.7	13.9	129.0	16.2	33.1	144.4	61.9	63.9	31.5	24.0
Toplica	675.6	7.1	28.8	129.4	17.1	31.7	114.6	82.7	59.4	18.9	19.3
Pirot	714.2	24.1	21.0	115.3	19.8	23.2	132.3	65.8	51.1	26.7	13.2
Jablanica	641.0	21.5	30.9	108.8	22.8	35.8	135.7	51.9	27.5	23.2	24.9
Pcinj	580.8	17.9	25.0	98.5	21.3	18.4	73.9	36.6	63.3	7.7	15.0
Niš	641.1	9.4	17.2	87.1	27.1	26.2	132.1	58.2	71.6	21.1	22.0

Table 3
Data on standardized incidence of most common malignancies in females for the year 2022 in Serbia.

District	All cancers (C00-C97)	Colon and rectal cancer (C18-C20)	Pancreatic cancer (C25)	Lung cancer (C34)	Breast cancer (2022) (C50)	Cervical cancer (2022) (C53)	Uterine cancer (2022) (C54)	Ovarian cancer (2022) (C56)	Bladder cancer (2022) (C67)	Brain cancer (C71)	Non-Hodgkin lymphoma (2022) (C82-C85)
West Bačka	897.2	93.9	20.0	144.4	144.4	57.0	30.0	36.2	32.4	20.2	21.5
North Bačka	903.1	105.6	19.8	203.2	203.2	37.8	39.2	39.6	23.8	8.5	13.0
North Banat	997.0	93.1	20.9	188.8	188.8	60.3	18.9	41.0	26.1	13.0	21.1
South Bačka	686.7	70.1	20.6	115.0	115.0	21.7	16.4	20.7	19.8	9.6	11.5
Middle Banat	824.4	94.2	20.7	163.2	163.2	39.4	35.4	23.6	33.8	8.7	13.0
South Banat	673.1	54.6	15.5	121.0	121.0	33.9	17.7	31.6	14.7	9.7	10.4
Srem	732.8	89.5	16.9	131.4	131.4	27.6	25.7	25.6	27.3	15.0	18.4
Mačva	514.6	37.3	14.0	108.4	137.2	30.2	19.2	20.1	23.9	7.9	10.5
Belgrade	548.4	43.4	21.8	135.6	135.6	27.6	14.8	20.7	16.7	11.9	10.1
Kolubara	610.7	56.3	18.5	159.5	141.5	31.3	24.2	25.9	13.5	10.2	7.4
Danube	535.1	53.6	19.0	120.7	126.1	32.9	34.8	16.5	21.8	19.9	18.7
Braničevo	512.6	63.6	9.8	119.5	106.3	25.2	27.3	31.4	26.2	10.7	8.6
Bor	646.9	50.9	15.7	131.3	112.3	61.1	41.1	33.5	23.0	15.4	19.8
Zlatibor	508.8	62.2	14.1	79.3	79.9	22.9	32.4	23.3	31.9	18.6	12.8
Morava	591.8	57.8	10.7	143.0	115.9	30.2	32.0	15.8	39.0	24.0	21.4
Sumadija	638.5	74.4	15.1	124.6	123.4	36.9	31.6	23.9	22.6	14.7	22.4
Moravica	508.3	48.6	16.9	123.4	126.0	21.9	32.2	36.3	15.6	11.0	7.3
Zaječar	546.5	48.6	19.5	134.0	99.9	49.7	43.2	17.9	7.5	9.6	8.5
Raška	518.3	49.9	14.1	119.6	131.2	25.7	35.4	20.5	16.0	15.0	4.8
Rasina	620.1	81.4	15.3	156.9	144.4	33.8	12.1	22.3	21.7	28.0	12.0
Toplica	621.4	64.7	5.0	181.2	114.6	68.4	35.6	18.6	15.1	20.7	8.0
Pirot	617.8	72.9	13.9	129.6	132.3	41.2	47.6	32.8	20.8	15.0	7.2
Jablanica	488.9	58.9	18.2	115.2	135.7	29.9	32.3	12.8	4.4	15.1	9.3
Pcinj	465.8	43.8	15.8	110.6	73.9	21.8	32.4	15.6	25.1	9.1	12.0
Niš	528.6	55.2	20.4	128.1	132.1	29.9	20.1	13.2	23.0	17.2	12.5

Table 4
Correlational analysis between water quality parameters (physicochemical characteristics and residual chlorine concentrations) and standardized cancer incidence in Serbia in 2022 of overall cancers and then most frequent cancer types in males.

Type of cancer (ICD-10 code)	Percentage of water not meeting physicochemical standards in 2013	Percentage of water not meeting physicochemical standards in 2021	Average percentage of water samples not meeting residual chlorine standards from 2017 to 2022	Average maximum residual chlorine levels measured from 2017 to 2022
All cancers (C00-C97)	r = 0.515 **p = 0.008**	r = 0.578 **p = 0.002**	r = 0.192 p = 0.358	r = −0.265 p = 0.201
Oral and pharyngeal cancer (C00-C10)	r = 0.159 p = 0.448	r = 0.285 p = 0.167	r = −0.367 p = 0.071	r = −0.157 p = 0.453
Gastric cancer (C16)	r = 0.395 p = 0.051	r = 0.350 p = 0.086	r = −0.146 p = 0.486	r = −0.152 p = 0.467
Colon and rectal cancer (C18-C20)	r = 0.434 **p = 0.030**	r = 0.526 **p = 0.007**	r = 0.098 p = 0.639	r = 0.001 p = 0.956
Pancreatic cancer (C25)	r = 0.315 p = 0.125	r = 0.232 p = 0.265	r = −0.230 p = 0.269	r = −0.131 p = 0.533
Laryngeal cancer (C32)	r = −0.217 p = 0.297	r = −0.051 p = 0.809	r = −0.020 p = 0.923	r = −0.041 p = 0.844
Lung cancer (C34)	r = 0.187 p = 0.370	r = 0.278 p = 0.178	r = 0.214 p = 0.303	r = 0.336 p = 0.101
Prostate cancer (C61)	r = 0.438 **p = 0.028**	r = 0.280 p = 0.174	r = −0.161 p = 0.433	r = −0.070 p = 0.737
Bladder cancer (C67)	r = −0.180 p = 0.388	r = −0.063 p = 0.763	r = 0.406 **p = 0.043**	r = 0.325 p = 0.113
Brain cancer (C71)	r = −0.296 p = 0.151	r = −0.001 p = 0.994	r = 0.258 p = 0.213	r = 0.194 p = 0.354
Overall leukemia (C91-95)	r = −0.152 p = 0.469	r = 0.049 p = 0.816	r = 0.046 p = 0.824	r = 0.014 p = 0.947

Table 5
Correlational analysis between water quality parameters (physicochemical characteristics and residual chlorine concentrations and standardized cancer incidence in Serbia in 2022 of overall cancers and then most frequent cancer types in females.

Type of cancer (ICD-10 code)	Percentage of water not meeting physicochemical standards in 2013	Percentage of water not meeting physicochemical standards in 2021	Average percentage of water samples not meeting residual chlorine standards from 2017 to 2022	Average maximum residual chlorine levels measured from 2017 to 2022
All cancers (C00-C97)	r = 0.678 **p < 0.001**	r = 0.755 **p < 0.001**	r = 0.221 p = 0.288	r = −0.210 p = 0.315
Colon and rectal cancer (C18-C20)	r = 0.470 **p = 0.018**	r = 0.534 **p = 0.005**	r = 0.175 p = 0.404	r = 0.120 p = 0.568
Pancreatic cancer (C25)	r = 0.198 p = 0.343	r = 0.406 **p = 0.044**	r = −0.249 p = 0.229	r = −0.086 p = 0.682
Lung cancer (C34)	r = 0.273 p = 0.186	r = 0.497 **p = 0.012**	r = −0.028 p = 0.892	r = −0.115 p = 0.584
Breast cancer (C50)	r = 0.143 p = 0.495	r = 0.190 p = 0.363	r = 0.021 p = 0.919	r = 0.111 p = 0.598
Cervical cancer (C53)	r = 0.307 p = 0.135	r = 0.426 **p = 0.033**	r = 0.023 p = 0.912	r = −0.055 p = 0.794
Uterine cancer (C54)	r = −0.057 p = 0.787	r = −0.038 p = 0.856	r = −0.254 p = 0.221	r = −0.426 **p = 0.033**
Ovarian cancer (C56)	r = 0.533 **p = 0.006**	r = 0.415 **p = 0.039**	r = −0.041 p = 0.844	r = 0.023 p = 0.912
Bladder cancer (C67)	r = 0.400 **p = 0.047**	r = 0.291 p = 0.158	r = −0.010 p = 0.962	r = −0.114 p = 0.588
Brain cancer (C71)	r = −0.256 p = 0.217	r = −0.015 p = 0.942	r = 0.081 p = 0.700	r = −0.032 p = 0.877
Non-Hodgkin lymphoma (C82-C85)	r = 0.431 **p = 0.030**	r = 0.391 p = 0.053	r = −0.080 p = 0.691	r = −0.090 p = 0.654

environmental factors are linked to a heightened incidence of cancer, further investigations to monitor the compliance to regulatory limits and possibly modify them are warranted (Vinceti et al., 2024, 2025; Zahra et al., 2025). By addressing these modifiable factors, the incidence of cancer could potentially be reduced.

4.2. Summary of the study's main findings

In order to ensure the most rigorous methodological approach, potential association were considered relevant only if a particular cancer type correlated with the percentage of unsatisfactory physicochemical water samples in both examined years, 2013 and 2021. Therefore, we found that exposure to water samples with unsatisfactory physicochemical characteristics from public water supply systems and water facilities is associated with an increased risk of various cancer types, including colon and rectal cancer in both sexes and ovarian cancer in females. The incidence rates of these four cancer types (all cancers in males and females, as well as colon cancer in both sexes) correlated with the percentage of water samples with unsatisfactory physicochemical characteristics for both examined years, 2013 and 2021. Next, brain tumors, lung cancer, and pancreatic cancer in males were not associated with exposure to poor physicochemical water quality. Finally, bladder cancer in males was associated with exposure to residual chlorine which surpass recommended concentrations.

4.3. Comparison with existing literature

Despite the correlation with maximal residual chlorine with bladder cancer incidence was weaker and much imprecise, still positive values could be noted. The percentage of non-compliant water samples may represent a more reliable variable for analysis, as a higher percentage may indicate that a larger proportion of district inhabitants is exposed to residual chlorine levels above standard reference value. In contrast, maximal concentration values may reflect a single measurement from one water source, potentially exposing only a limited number of individuals.

A study from Arizona aimed to investigate associations between nine water contaminants and various types of malignancies by performing correlational analyses. The analyzed cancer types included lung, kidney, colorectal, liver, pancreatic, stomach, prostatic, hematological, female breast, gynecological, bladder, and skin melanoma. Several water contaminants were found to be positively correlated with an increased incidence of both bladder and pancreatic cancers (Garcia and Matthews, 2024). Hadkhale et al. investigated the association between groundwater radon exposure and lung cancer risk. Their analysis revealed that municipalities within hospital districts exhibiting the highest levels of radon exposure had significantly higher lung cancer incidence rates compared to those with low or no exposure (Hadkhale et al., 2022).

Exposure to various toxic substances in drinking water represents a significant public health issue. Hungary, for instance, faced a major problem with As in drinking water. After becoming a member of the EU, Hungary mitigated As concentrations in water, which consequently reduced cancer risk (Pál et al., 2022). Koivusalo et al. conducted a historical cohort study in Finland and, using data on $KMnO_4$ values and chlorine concentrations, demonstrated a positive association between these compounds and the incidence of colon cancer (Koivusalo et al., 1997). Picetti et al. performed a systematic review and reported that nitrates—whose levels exceed recommended concentrations in some districts of Serbia—are associated with an increased risk of gastric cancer (Picetti et al., 2022). Krajewski et al. reported association between As exposure and appearance of bladder, colorectal, and kidney cancers (Krajewski et al., 2021). Jovanovic et al. analyzed As concentrations in various villages and cities primarily located in Middle Banat, South Bačka, and North Bačka, all three regions of Vojvodina, and reported that more than 60 % of the samples exceeded the recommended EU and Serbian standards (Jovanovic et al., 2011). Vojvodina districts are not the only which have problem with high As levels, namely, measurement of samples taken from the Great Morava River exceeded the WHO recommended value of 10 μg/L for drinking water (Devic et al., 2014). Next, groundwater analyses in the Rasina district revealed high levels of cadmium (Cd), Pb, and Ni (Devic et al., 2014) and groundwater pollution with higher levels of As and Cu due to mining activities has been reported in Eastern Serbia (Adamovic et al., 2022). Additionally, in community water systems across 19 states in the United States using data from the Centers for Disease Control and Prevention (CDC), an increased risk of colon cancer in the group with the highest (fourth) quartile compared to the first quartile of As exposure was reported (Krajewski et al., 2021). Fakhri et al. analyzed concentrations of Hg, As, zinc (Zn), Pb, and copper (Co) in tap water from Ilam city in Iran and reported that all examined metals and metalloids were above the recommended Iran and WHO standards, posing a significant cancer risk (Fakhri et al., 2018).

Bladder cancer in males showed a positive correlation with the percentage of water samples not meeting residual chlorine standards. Whether exposure to excess residual chlorine or disinfection by-products such as trihalomethanes is associated with an increased risk of bladder cancer remains a relevant and debated topic, as some studies have indicated a potential link (Bove et al., 2007), while others have not (Helte et al., 2022; Shi et al., 2024b). Téllez Tovar et al. aimed to examine the association between trihalomethane exposure through inhalation during showers and lifetime cancer risk, concluding that such exposure increases cancer risk (Téllez Tovar and Rodríguez Susa, 2021). This finding is particularly significant because dermal exposure to trihalomethanes carries a cancer risk comparable to ingestion (Ab Jalil et al., 2021; Tafesse et al., 2023). Inhalation and ingestion allow chlorine and its by-products to come into contact with the upper airways and the initial part of the alimentary tract.

It has been reported that trihalomethane exposure increases the risk of urinary bladder cancer (Abbasnia et al., 2019; Bove et al., 2007; Evlampidou et al., 2020). Evlampidou et al. analyzed 13 years of trihalomethane level data across 26 EU member countries, covering three-quarters of the EU population, and noted that regulating water quality could prevent bladder cancer cases (Evlampidou et al., 2020). Additionally, a study from Madrid indicated that individuals with high tap water consumption may face a greater cancer risk than deemed acceptable (Almonacid Garrido et al., 2024). Exposure to disinfection by-product has been associated with dose-dependent increase cancer risk, including bladder and colon cancer especially in males than females (Shi et al., 2024a). In a recent systematic review by Helte et al., which included 29 published studies on various malignancies and trihalomethanes, the authors reported that exposure to trihalomethanes was associated not only with bladder cancer but also with colorectal cancer (Helte et al., 2025).

4.4. Limitations, strengths and future perspectives

As a limitation, we acknowledge that our study is constrained by the concentrations of other substances, which frequently exceed the upper recommended limit. In the future, we anticipate more studies examining the relation between specific toxic compounds and health risks in the investigated communities. One of the main strengths of this study is that it encompasses the population of the entire country. Additionally, the percentage of water samples that did not meet the standards for physicochemical properties is a non-specific parameter; we lack data on whether the water was merely turbid or whether several substances exceeded recommended concentrations—both of which would result in the sample being classified as non-compliant. Furthermore, individual data of metals and metalloids with toxicologic relevance are note available and could not be evaluated. As is known to pose significant concerns in Vojvodina district (Jovanovic et al., 2011). However, since it is not measured using a standardized procedure, it could not be specifically evaluated, representing another limitation of this study. On the other hand, the finding that in certain regions up to 95 % of water samples failed to meet physicochemical standards allows us to reasonably speculate that a large portion of the population in those areas was exposed to contaminated water.

Another limitation is the lack of assessment of concentrations of disinfection by-products such as trihalomethanes that specifically showed increased risk of some types of cancer and especially in males (Shi et al., 2024a), hampering a clear comparison with study findings. In addition, consumption of foodstuffs which are contaminated with some pollutants which may be found in water such as heavy metals can rise risk of cancer as well (Kiani et al., 2021). However, no data on food contamination and intake in the investigated populations are available. Finally, by using water quality data collected over several years, we minimized the potential impact of seasonal variations such as rainfall and temperature fluctuations (Ayejoto et al., 2023). Finally, the complexity of this topic is reflected not only in the need to reduce hazardous substances such as Cd, As, and nitrates, but also in the importance of optimizing the concentrations of beneficial elements like sodium (Na^+), magnesium (Mg^{2+}), calcium (Ca^{2+}), and zinc (Zn^{2+}) (Agbasi et al., 2024, 2025).

5. Conclusions

Although water quality in Serbia is comparable with water quality in EU members, there are some regional variations in water quality. The

percentage of water that does not meet adequate physicochemical standards significantly varied among Serbian districts in 2013 and 2021. The quality of water to which people are exposed should be a primary focus of future preventive measures. By improving the physicochemical properties of water, we could potentially reduce the incidence of certain malignancies. Lung cancer was the most common cancer type in males, while breast cancer was the leading type in females. The study indicates that exposure to water that does not meet adequate physicochemical standards may be associated with an increased risk of various cancer types—including any cancer, as well as colon and rectal cancer in males, and any cancer, colon and rectal cancer, and ovarian cancer in females. Surpass levels of residual chlorine in water are linked with bladder neoplasm in males. As a future perspective, studies investigating specific contaminants (including heavy metals, metalloids, and disinfection by-products) across all districts should be conducted to clarify those primarily associated with the occurrence of specific malignancies.

CRediT authorship contribution statement

Ana Cirovic: Writing – review & editing, Methodology. **Nemanja Stojilovic:** Writing – review & editing, Writing – original draft, Investigation. **Riccardo Mazzoli:** Writing – review & editing, Visualization, Investigation. **Aleksandar Cirovic:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Tommaso Filippini:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The authors confirm that the data supporting the findings of this study are available within the article.

References

Ab Jalil, M.F., Hamidin, N., Gunny, A.A.N., Kamarudzaman, A.N., Gopinath, S.C.B., 2021. Potential risks assessment of rrihalomethanes in drinking water supply. J. Water Chem. Technol. 43, 468–474. https://doi.org/10.3103/S1063455X21060060.

Abbasnia, A., Mahboobeh, G., Nader, Y., Shahrokh, N., Majid, R., Hamed, S., et al., 2019. Prediction of human exposure and health risk assessment to trihalomethanes in indoor swimming pools and risk reduction strategy. Hum. Ecol. Risk Assess. 25, 2098–2115. https://doi.org/10.1080/10807039.2018.1488582.

Abu, M., Egbueri, J.C., Agbasi, J.C., 2025. Kriging-interpolated mapping and predictive modeling of groundwater F− and NO3− contamination with chemometric and health risk assessments in Ghana's Birimian Province. Environ. Geochem. Health 47, 165. https://doi.org/10.1007/s10653-025-02453-5.

Adamovic, D., Ishiyama, D., Kawaraya, H., Ogawa, Y., Stevanovic, Z., 2022. Geochemical characteristics and estimation of groundwater pollution in catchment areas of Timok and Pek Rivers, Eastern Serbia: determination of early-stage groundwater pollution in mining areas. Groundw. Sustain. Dev. 16, 100719. https://doi.org/10.1016/j.gsd.2021.100719.

Agbasi, J.C., Alkasimi, A., Turki, A.F., Abba, S.I., Khan, M.Y.A., Egbueri, J.C., 2025. Reimagining water quality assessment: a nutritional indexing perspective for drinking water resources management. Int. J. Environ. Anal. Chem. 1–27. https://doi.org/10.1080/03067319.2025.2482187.

Agbasi, J.C., Egbueri, J.C., Alghamdi, A.A., Ahmad, V., Al-Thawadi, S., Khan, M.Y.A., et al., 2024. Analytical examination of the nutritional status of drinking water resources: a first case application in Africa. Anal. Lett. 1–17. https://doi.org/10.1080/00032719.2024.2426041.

Alimam, W., Auvinen, A., 2025. Cancer risk due to ingestion of naturally occurring radionuclides through drinking water: a systematic review. Sci. Total Environ. 968, 178849. https://doi.org/10.1016/j.scitotenv.2025.178849.

Almonacid Garrido, M.C., Villanueva-Suárez, M.J., Álamo Gómez, A., Garcia-Alonso, A., Tenorio Sanz, M.D., 2024. Trihalomethane levels in municipal drinking water of Madrid (Spain) and health risk assessment for oral exposure. Expo. Health 16, 911–924. https://doi.org/10.1007/s12403-023-00599-0.

Antonijevic, E., Mandinic, Z., Curcic, M., Djukic-Cosic, D., Milicevic, N., Ivanovic, M., et al., 2016. "Borderline" fluorotic region in Serbia: correlations among fluoride in drinking water, biomarkers of exposure and dental fluorosis in schoolchildren. Environ. Geochem. Health 38, 885–896. https://doi.org/10.1007/s10653-015-9769-x.

Aralu, C.C., Okoye, P.A.C., Abugu, H.O., Ochiagha, K.E., Egbueri, J.C., 2024. Evaluating the seasonal variations of risks associated with potentially toxic elements in underground water sources near a dumpsite in Awka, Nigeria. J. Hazard Mater. 15, 100440. https://doi.org/10.1016/j.hazadv.2024.100440.

Ayejoto, D.A., Egbueri, J.C., Agbasi, J.C., Omeka, M.E., Unigwe, C.O., Nwazelibe, V.E., et al., 2023. Influence of seasonal changes on the quality of water resources in Southwestern Nigeria: a review. In: Egbueri, J.C., Ighalo, J.O., Pande, C.B. (Eds.), Climate Change Impacts on Nigeria: Environment and Sustainable Development. Springer International Publishing, Cham, pp. 423–447. https://doi.org/10.1007/978-3-031-21007-5_22.

Beane Freeman, L.E., Cantor, K.P., Baris, D., Nuckols, J.R., Johnson, A., Colt, J.S., et al., 2017. Bladder cancer and water disinfection by-product exposures through multiple routes: a population-based case-control study (New England, USA). Environ. Health Perspect. 125, 067010. https://doi.org/10.1289/ehp89.

Bijelovic, S., Grossi, V., Shinee, E., Schmoll, O., Jovanovic, D., Paunovic, K., et al., 2022. Water, sanitation, and hygiene services in health care facilities in the Autonomous Province of Vojvodina, Serbia. J. Water Health 20, 12–22. https://doi.org/10.2166/wh.2021.063.

Bouselsal, B., Satouh, A., Egbueri, J.C., Hashim, M.A., Arafat, A.A., Paramasivam, P., et al., 2025. Groundwater for drinking and sustainable agriculture and public health hazards of nitrate: developmental and sustainability implications for an arid aquifer system. Results Eng. 25, 104160. https://doi.org/10.1016/j.rineng.2025.104160.

Bove Jr., G.E., Rogerson, P.A., Vena, J.E., 2007. Case-control study of the effects of trihalomethanes on urinary bladder cancer risk. Arch. Environ. Occup. Health 62, 39–47. https://doi.org/10.3200/aeoh.62.1.39-47.

Bray, F., Laversanne, M., Sung, H., Ferlay, J., Siegel, R.L., Soerjomataram, I., et al., 2024. Global cancer statistics 2022: GLOBOCAN estimates of incidence and mortality worldwide for 36 cancers in 185 countries. CA Cancer J. Clin. 74, 229–263. https://doi.org/10.3322/caac.21834.

Carvalho, L., Mackay, E.B., Cardoso, A.C., Baattrup-Pedersen, A., Birk, S., Blackstock, K. L., et al., 2019. Protecting and restoring Europe's waters: an analysis of the future development needs of the Water Framework Directive. Sci. Total Environ. 658, 1228–1238. https://doi.org/10.1016/j.scitotenv.2018.12.255.

Cirovic, A., Cirovic, A., 2022. Iron deficiency as promoter of heavy metals-induced acute myeloid leukemia. Leuk. Res. 112, 106755. https://doi.org/10.1016/j.leukres.2021.106755.

Cirovic, A., Satarug, S., 2024. Toxicity tolerance in the carcinogenesis of environmental cadmium. Int. J. Mol. Sci. 25, 1851. https://doi.org/10.3390/ijms25031851.

Deiana, G., Filippini, T., Dettori, M., Vinceti, M., Azara, A., 2025. Exposure to disinfection by-products and risk of birth defects: a systematic review and dose-response meta-analysis. Sci. Total Environ. 985, 179693. https://doi.org/10.1016/j.scitotenv.2025.179693.

Devic, G., Djordjevic, D., Sakan, S., 2014. Natural and anthropogenic factors affecting the groundwater quality in Serbia. Sci. Total Environ. 468–469, 933–942. https://doi.org/10.1016/j.scitotenv.2013.09.011.

Devic, G., Sakan, S., Dordevic, D., 2016. Assessment of the environmental significance of nutrients and heavy metal pollution in the river network of Serbia. Environ. Sci. Pollut. Res. Int. 23, 282–297. https://doi.org/10.1007/s11356-015-5808-5.

Egbueri, J., Agbasi, J., Ighalo, J.O., Uwajingba, H., Abba, S., 2025a. Lead, nickel, arsenic, and chromium contamination in Nigerian groundwater: sources, potential impacts, and removal techniques. In: Ali, S., Negm, A. (Eds.), Groundwater in Developing Countries. Springer, Nature Switzerland, pp. 327–355. https://doi.org/10.1007/978-3-031-79122-2_14.

Egbueri, J.C., 2023. A multi-model study for understanding the contamination mechanisms, toxicity and health risks of hardness, sulfate, and nitrate in natural water resources. Environ. Sci. Pollut. Res. Int. 30, 61626–61658. https://doi.org/10.1007/s11356-023-26396-5.

Egbueri, J.C., Aj, C., Ali, K.M.Y., As, I., Ta, F., ElKashouty, M., 2025b. Assessing the environmental, health, and food security Implications of heavy metals in irrigation water: a multi-index analytical framework. Anal. Lett. 1–36. https://doi.org/10.1080/00032719.2025.2484451.

Evlampidou, I., Font-Ribera, L., Rojas-Rueda, D., Gracia-Lavedan, E., Costet, N., Pearce, N., et al., 2020. Trihalomethanes in drinking water and bladder cancer burden in the European Union. Environ. Health Perspect. 128, 17001. https://doi.org/10.1289/EHP4495.

Fakhri, Y., Saha, N., Ghanbari, S., Rasouli, M., Miri, A., Avazpour, M., et al., 2018. Carcinogenic and non-carcinogenic health risks of metal (oid) s in tap water from Ilam city, Iran. Food Chem. Toxicol. 118, 204–211. https://doi.org/10.1016/j.fct.2018.04.039.

Fantuzzi, G., Aggazzotti, G., Righi, E., Predieri, G., Giacobazzi, P., Kanitz, S., et al., 2007. [Exposure to organic halogen compounds in drinking water of 9 Italian regions:

exposure to chlorites, chlorates, trihalomethanes, trichloroethylene and tetrachloroethylene]. Ann Ig 19, 345–354.
Garcia, D., Matthews, T., 2024. Contaminated drinking water and its effect on cancer. ACS ES&T Water 4, 3340–3347. https://doi.org/10.1021/acsestwater.4c00210.
Garcia-Villanova, R.J., Oliveira, Dantas Leite MV., Hernandez Hierro, J.M., de Castro Alfageme, S., Garcia Hernandez, C., 2010. Occurrence of bromate, chlorite and chlorate in drinking waters disinfected with hypochlorite reagents. Tracing their origins. Sci. Total Environ. 408, 2616–2620. https://doi.org/10.1016/j.scitotenv.2010.03.011.
Hadkhale, K., Atosuo, J., Putus, T., 2022. Groundwater radon exposure and risk of lung cancer: a population-based study in Finland. Front. Oncol. 12, 935687. https://doi.org/10.3389/fonc.2022.935687.
Helte, E., Säve-Söderbergh, M., Larsson, S.C., Martling, A., Åkesson, A., 2023. Disinfection by-products in drinking water and risk of colorectal cancer: a population-based cohort study. J. Natl. Cancer Inst. 115, 1597–1604. https://doi.org/10.1093/jnci/djad145.
Helte, E., Säve-Söderbergh, M., Ugge, H., Fall, K., Larsson, S.C., Åkesson, A., 2022. Chlorination by-products in drinking water and risk of bladder cancer – a population-based cohort study. Water Res. 214, 118202. https://doi.org/10.1016/j.watres.2022.118202.
Helte, E., Soderlund, F., Save-Soderbergh, M., Larsson, S.C., Akesson, A., 2025. Exposure to drinking water trihalomethanes and risk of cancer: a systematic review of the epidemiologic evidence and dose-response meta-analysis. Environ. Health Perspect. 133, 16001. https://doi.org/10.1289/EHP14505.
Jauniaux, E., Jeremiah, L., Richardson, B., Rogozinska, E., 2024. Exposure to drinking water pollutants and non-syndromic birth defects: a systematic review and meta-analysis synthesis. BMJ Open 14, e084122. https://doi.org/10.1136/bmjopen-2024-084122.
Jovanovic, D., Jakovljević, B., Rašić-Milutinović, Z., Paunović, K., Peković, G., Knezević, T., 2011. Arsenic occurrence in drinking water supply systems in ten municipalities in Vojvodina Region, Serbia. Environ. Res. 111, 315–318. https://doi.org/10.1016/j.envres.2010.11.014.
Jovanovic, D., Rasic-Milutinovic, Z., Paunovic, K., Jakovljevic, B., Plavsic, S., Milosevic, J., 2013. Low levels of arsenic in drinking water and type 2 diabetes in Middle Banat region, Serbia. Int. J. Hyg Environ. Health 216, 50–55. https://doi.org/10.1016/j.ijheh.2012.01.001.
Jovanovic, D.D., Paunovic, K., Manojlovic, D.D., Jakovljevic, B., Rasic-Milutinovic, Z., Dojcinovic, B.P., 2012. Arsenic in drinking water and acute coronary syndrome in Zrenjanin municipality, Serbia. Environ. Res. 117, 75–82. https://doi.org/10.1016/j.envres.2012.04.016.
Karmakar, B.K.S.M., Krishan, C.B., Kumar, S.S., Ej, C., Kumar, G.S., et al., 2023. Investigation of the hydrogeochemistry, groundwater quality, and associated health risks in industrialized regions of Tripura, northeast India. Environ. Forensics 24, 285–306. https://doi.org/10.1080/15275922.2021.2006363.
Kiani, B., Hashemi Amin, F., Bagheri, N., Bergquist, R., Mohammadi, A.A., Yousefi, M., et al., 2021. Association between heavy metals and colon cancer: an ecological study based on geographical information systems in North-Eastern Iran. BMC Cancer 21, 414. https://doi.org/10.1186/s12885-021-08148-1.
Knežević, T., 2014. [Report on the Health of Drinking Water from Public Waterworks and Water Facilities in the Republic of Serbia for 2013]. Institute of Public Health of Serbia "Dr Milan Jovanović Batut, Belgrade.
Knežević, T., 2018. [Report on the Health Safety of Drinking Water from Public Water Supply Systems and Water Facilities in the Republic of Serbia for 2017]. Institute of Public Health of Serbia "Dr Milan Jovanović Batut, Belgrade.
Knežević, T., 2022. [Report on the Health Safety of Drinking Water from Public Water Supply Systems and Water Facilities in the Republic of Serbia for 2021]. Institute of Public Health of Serbia "Dr Milan Jovanović Batut, Belgrade.
Koivusalo, M., Pukkala, E., Vartiainen, T., Jaakkola, J.J., Hakulinen, T., 1997. Drinking water chlorination and cancer-a historical cohort study in Finland. Cancer Causes Control 8, 192–200. https://doi.org/10.1023/a:1018420229802.
Krajewski, A.K., Jimenez, M.P., Rappazzo, K.M., Lobdell, D.T., Jagai, J.S., 2021. Aggregated cumulative county arsenic in drinking water and associations with bladder, colorectal, and kidney cancers, accounting for population served. J. Expo. Sci. Environ. Epidemiol. 31, 979–989. https://doi.org/10.1038/s41370-021-00314-8.
Li, P., Wu, J., 2019. Drinking water quality and public health. Expo. Health 11, 73–79. https://doi.org/10.1007/s12403-019-00299-8.
Mazhar, M.A., Khan, N.A., Ahmed, S., Khan, A.H., Hussain, A., Rahisuddin, et al., 2020. Chlorination disinfection by-products in municipal drinking water – a review. J Clin Prod 273, 123159. https://doi.org/10.1016/j.jclepro.2020.123159.
Miljus, D., Zivkovic Perisic, S., 2024. Malignant tumors in Repubic of Serbia 2022. Institute of Public Health of Serbia “Dr Milan Jovanović Batut”. Belgrade, p. 72. https://www.batut.org.rs/download/publikacije/MaligniTumoriURepubliciSrbiji2022.pdf. (Accessed April 3, 2025).
Najafi Saleh, H., Valipoor, S., Zarei, A., Yousefi, M., Baghal Asghari, F., Mohammadi, A. A., et al., 2020. Assessment of groundwater quality around municipal solid waste landfill by using Water Quality Index for groundwater resources and multivariate statistical technique: a case study of the landfill site, Qaem Shahr City, Iran. Environ. Geochem. Health 42, 1305–1319. https://doi.org/10.1007/s10653-019-00417-0.
Pál, L., Jenei, T., McKee, M., Kovács, N., Vargha, M., Bufa-Dőrr, Z., et al., 2022. Health and economic gain attributable to the introduction of the World Health Organization’s drinking water standard on arsenic level in Hungary: a nationwide retrospective study on cancer occurrence and ischemic heart disease mortality. Sci. Total Environ. 851, 158305. https://doi.org/10.1016/j.scitotenv.2022.158305.
Pande, C.B., Tolche, A.D., Egbueri, J.C., Mohd Sidek, L., Singh, R., Mishra, A.P., et al., 2025. Implications of seasonal variations of hydrogeochemical analysis using GIS, WQI, and statistical analysis method for the semi-arid region. Appl. Water Sci. 15, 80. https://doi.org/10.1007/s13201-025-02387-4.
Picetti, R., Deeney, M., Pastorino, S., Miller, M.R., Shah, A., Leon, D.A., et al., 2022. Nitrate and nitrite contamination in drinking water and cancer risk: a systematic review with meta-analysis. Environ. Res. 210, 112988. https://doi.org/10.1016/j.envres.2022.112988.
Rajovic, N., Grubor, N., Cirkovic, A., Maheswaran, R., Bath, P.A., Green, D., et al., 2024. Insights into relationship of environmental inequalities and multimorbidity: a population-based study. Environ. Health 23, 99. https://doi.org/10.1186/s12940-024-01133-8.
Righi, E., Bechtold, P., Tortorici, D., Lauriola, P., Calzolari, E., Astolfi, G., et al., 2012. Trihalomethanes, chlorite, chlorate in drinking water and risk of congenital anomalies: a population-based case-control study in Northern Italy. Environ. Res. 116, 66–73. https://doi.org/10.1016/j.envres.2012.04.014.
Rowbottom, J., Graversgaard, M., Wright, I., Dudman, K., Klages, S., Heidecke, C., et al., 2022. Water governance diversity across Europe: does legacy generate sticking points in implementing multi-level governance? J. Environ. Manag. 319, 115598. https://doi.org/10.1016/j.jenvman.2022.115598.
Shi, J., Zhang, K., Xiao, T., Yang, J., Sun, Y., Yang, C., et al., 2024a. Exposure to disinfection by-products and risk of cancer: a systematic review and dose-response meta-analysis. Ecotoxicol. Environ. Saf. 270, 115925. https://doi.org/10.1016/j.ecoenv.2023.115925.
Shi, Y., Xia, W., Liu, H., Liu, J., Cao, S., Fang, X., et al., 2024b. Trihalomethanes in global drinking water: distributions, risk assessments, and attributable disease burden of bladder cancer. J. Hazard Mater. 469, 133760. https://doi.org/10.1016/j.jhazmat.2024.133760.
Singh, G., Wani, O.A., Egbueri, J.C., Salaria, A., Singh, H., 2023. Seasonal variation of the quality of groundwater resources for human consumption and industrial purposes in the central plain zone of Punjab, India. Environ. Monit. Assess. 195, 1454. https://doi.org/10.1007/s10661-023-12039-2.
Tafesse, N., Porcelli, M., Hirpessa, B.B., Gasana, J., Padhi, R.K., Garie, S.R., et al., 2023. Exposure and carcinogenic risk assessment of trihalomethanes (THMs) for water supply consumers in Addis Ababa, Ethiopia. Toxicol. Rep. 10, 261–268. https://doi.org/10.1016/j.toxrep.2023.02.004.
Tanwar, D., Tyagi, S., Sarma, K., 2024. Evaluating seasonal variability of hydrogeochemistry, qualitative and corrosion-scaling effects of groundwater in southern region of NCT of Delhi, India. Groundw. Sustain. Dev. 27, 101331. https://doi.org/10.1016/j.gsd.2024.101331.
Téllez Tovar, S.S., Rodríguez Susa, M., 2021. Cancer risk assessment from exposure to trihalomethanes in showers by inhalation. Environ. Res. 196, 110401. https://doi.org/10.1016/j.envres.2020.110401.
van den Berg, H., Rickert, B., Lock-Wah-Hoon, J., Jovanovic, D., Bijelovic, S., Gligorijevic, S., et al., 2023. Experiences from integrating water and sanitation safety planning in small systems in rural Serbia. J. Water Health 21, 1772–1783. https://doi.org/10.2166/wh.2023.204.
Veskovic, J., Dersek-Timotic, I., Lucic, M., Miletic, A., Dolic, M., Razic, S., et al., 2024. Entropy-weighted water quality index, hydrogeochemistry, and Monte Carlo simulation of source-specific health risks of groundwater in the Morava River plain (Serbia). Mar. Pollut. Bull. 201, 116277. https://doi.org/10.1016/j.marpolbul.2024.116277.
Villanueva, C.M., Evlampidou, I., Ibrahim, F., Donat-Vargas, C., Valentin, A., Tugulea, A. M., et al., 2023. Global assessment of chemical quality of drinking water: the case of trihalomethanes. Water Res. 230, 119568. https://doi.org/10.1016/j.watres.2023.119568.
Villanueva, C.M., Gracia-Lavedan, E., Bosetti, C., Righi, E., Molina, A.J., Martin, V., et al., 2017. Colorectal cancer and long-term exposure to trihalomethanes in drinking water: a multicenter case-control study in Spain and Italy. Environ. Health Perspect. 125, 56–65. https://doi.org/10.1289/EHP155.
Vinceti, M., Mazzoli, R., Wise, L.A., Veneri, F., Filippini, T., 2025. Calling for a comprehensive risk assessment of selenium in drinking water. Sci. Total Environ. 966, 178700. https://doi.org/10.1016/j.scitotenv.2025.178700.
Vinceti, M., Vicentini, M., Wise, L.A., Sacchettini, C., Malagoli, C., Ballotari, P., et al., 2018. Cancer incidence following long-term consumption of drinking water with high inorganic selenium content. Sci. Total Environ. 635, 390–396. https://doi.org/10.1016/j.scitotenv.2018.04.097.
Vinceti, S.R., Veneri, F., Filippini, T., 2024. Water fluoridation between public health and public law: an assessment of regulations across countries and their preventive medicine implications. Ann Ig 36, 261–269. https://doi.org/10.7416/ai.2024.2594.
WHO, 2022. Guidelines for drinking-water quality: fourth edition incorporating the first and second addenda. In: Environment Climate Change and Health (ECH), Water Sanitation Hygiene and Health (WSH). World Health Organization, Geneva, p. 614.
Wuijts, S., Claessens, J., Farrow, L., Doody, D.G., Klages, S., Christophoridis, C., et al., 2021. Protection of drinking water resources from agricultural pressures: effectiveness of EU regulations in the context of local realities. J. Environ. Manag. 287, 112270. https://doi.org/10.1016/j.jenvman.2021.112270.
Yassin, M.A., Abba, S.I., Shah, S.M., Usman, A.G., Egbueri, J.C., Agbasi, J.C., et al., 2024. Toward decontamination in coastal regions: groundwater quality, fluoride, nitrate, and human health risk assessments within multi-aquifer Al-Hassa, Saudi Arabia. Water (Lond. 1974) 16, 1401. https://doi.org/10.3390/w16101401.
Zahra, A., Ali, M., Ali, N., Khan, A., Zairov, R., Sinyashin, O., et al., 2025. A comprehensive analysis of the impact of arsenic, fluoride, and nitrate-nitrite dynamics on groundwater quality and its health implications. J. Hazard Mater. 487, 137093. https://doi.org/10.1016/j.jhazmat.2025.137093.