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Emerging contaminants in drinking water sources and their implications for public health

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Abstract

This study investigates the occurrence, seasonal variation, and potential public health implications of emerging contaminants in drinking water sources. A computational evaluation was performed on 72 simulated water samples from six surface water and six ground water monitoring locations. Differences in concentrations, detection frequencies and seasonal patterns were assessed for six contaminants including pharmaceuticals, pesticides, bisphenol A and per and polyfluoroalkyl substances. The surface waters had higher median concentrations of carbamazepine (29.37 ng/L), diclofenac (27.40 ng/L) and bisphenol A (37.07 ng/L) than the groundwaters. Seasonal analysis shows high levels of contaminants during wet conditions, especially in surface water. Selected chemicals exceeded reference-dose screening thresholds under the simulated conditions. Human health screening yielded higher body-weight adjusted exposure estimates for children than adults. These findings emphasize the need for integrated contaminant monitoring, seasonal evaluation, and population-specific exposure assessment in identifying potential drinking water safety issues and informing future field investigations.

Keywords: Emerging Contaminants, Drinking water quality, Surface water and groundwater, Seasonal variation, Human health risk assessment

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Introduction

Drinking water quality is an important public health concern because contaminated water can expose people to harmful chemical and biological substances over long periods. Rivers, reservoirs, lakes, and groundwater systems are widely used as sources of drinking water for urban and rural populations. These water sources are increasingly affected by industrial discharge, agricultural activities, domestic wastewater, and the improper disposal of chemical products. Emerging contaminants are substances that are not routinely monitored in many water quality programmes but may cause environmental or health concerns. They include pharmaceutical residues, personal care products, pesticides, endocrine-disrupting chemicals, per- and polyfluoroalkyl substances (PFAS), and microplastics. Investigations of drinking water sources have identified several emerging contaminants that may contribute to long-term human exposure (Elliott *et al*., 2025). Unlike conventional water pollutants, some emerging contaminants can occur at very low concentrations and may pass through existing water treatment processes. Their continuous release into aquatic environments creates a need for improved monitoring and evaluation of drinking water safety.

Pharmaceutical residues and personal care products are important groups of emerging contaminants that reach water systems through domestic wastewater, health care activities and industrial discharges. Typical items are antibiotics, pain killers and other chemical substances used in medical or personal care applications. Pharmaceutical compounds have been shown to persist through conventional treatment processes in studies of both raw and treated drinking water (Muambo *et al*., 2024). Their occurrence depends on wastewater discharge, water source features, chemical stability, and treatment efficiency. In general, human activities directly affect surface water sources, while groundwater contamination can occur through infiltration, contaminated recharge and interaction with contaminated surface waters. Research studies on urban water environments in India have reported presence of emerging organic contaminants in surface water and groundwater systems (Brauns *et al*., 2024). These results indicate that the distribution of contaminants may differ between water sources, even within the same geographical area. Understanding these differences is crucial for tracking contamination pathways and for selecting appropriate water management options.

Other challenges to drinking water quality assessment include persistent chemicals and plastic particles. PFAS are used in a variety of industrial and consumer products for their resistance to heat, water and chemical degradation. But their persistence in the environment and potential health impacts have raised concerns about their presence in drinking water. Investigations of PFAS in raw and treated drinking water have shown that the chemical occurrence and removal behavior varies across treatment systems (Sadia *et al*., 2023). Other emerging

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substances, such as industrial additives and chemicals associated with modern electronic products, are also being identified in drinking water monitoring programs (Sim *et al*., 2025). Another group of contaminants are microplastics, small plastic particles that enter water sources by way of wastewater, surface runoff, atmospheric deposition and the breakdown of larger plastic materials. During research on different drinking water sources in India, microplastics have been reported in groundwater, surface water and stored water (Pavithra *et al*., 2024). The joint monitoring and risk interpretation of these contaminants are more complicated than the conventional assessment of water quality due to the diversity of physical and chemical properties.

The public health implications of emerging contaminants depend on their concentrations, exposure duration, drinking water consumption, and toxicological characteristics. Long-term exposure may be particularly important for substances associated with endocrine disruption, organ toxicity, or other chronic health effects. Investigations of pharmaceutical and personal care product contamination in the Musi River have highlighted the relevance of human activities to emerging contaminant occurrence in aquatic environments (Konda *et al*., 2024). However, contaminant detection alone does not establish the magnitude of human health risk because exposure levels and chemical-specific toxicity must also be considered. Many existing investigations focus on selected chemicals or individual water sources, leaving a need for integrated comparisons of contaminant distribution, seasonal variation, and population-specific exposure. This study develops a comparative assessment framework for emerging contaminants in drinking water sources of surface water and ground water. The research design includes targeted chemical analysis, microplastic characterization, seasonal monitoring and human health risk assessment. The main aim is to investigate the differences in the presence of contaminants between the sources of drinking water and seasons and to identify which of the measured substances can be of greater concern in the protection of drinking water and public health management.

Methodology

The study is designed as a comparative environmental monitoring investigation of emerging contaminants in surface water and groundwater used for drinking water supply. The sampling framework consists of 12 monitoring locations, 6 surface water sites and 6 groundwater sites within a defined study region. For rivers and reservoirs, abstraction points are locations of surface water. For wells used for domestic drinking water supply, abstraction points are locations of ground water. The sites have been chosen to reflect varying degrees of nearby residential, agricultural and industrial activity. Each site is given a unique identification code and is recorded by geographical position, surrounding land use, water source characteristics and potential contamination pathways.

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Seasonal water quality studies have shown the need to assess the occurrence of pesticides in surface water and drinking water wells (Kruć-Fijałkowska *et al*., 2022). The proposed sampling program includes three visits in the dry season and three in the wet season, providing 72 primary water samples across all locations. For the analytical quality assessment, additional blanks of the field and duplicate samples are introduced. This sampling design allows us to analyze differences between water source categories and seasonal conditions, by means of repeated observations at the same monitoring locations.

Water samples are collected in pre-cleaned containers according to the contaminants being analyzed. Different sample containers are used for the analysis of organic chemicals, PFAS and microplastic particles, decreasing the possibility of contamination and enhancing analytical robustness. Samples for dissolved organic compounds are collected in amber glass bottles. Samples for PFAS are collected in suitable PFAS-free containers with materials screened for potential analytical interference. Samples of microplastics are collected in cleaned glass or metal equipment and stored apart from chemical samples. Water temperature, pH, electrical conductivity, dissolved oxygen and turbidity are measured during each sampling visit to describe the general water quality conditions. Seasonal studies of endocrine disrupting chemicals in drinking water systems have shown that the occurrence of contaminants may vary with environmental and water supply conditions (Kumawat *et al*., 2022). Meteorological records and rainfall information are also included to examine possible relationships between seasonal changes and measured contaminant levels. Samples are transported under temperature-controlled conditions and processed within method-specific holding times. The sampling design separates the effects of water source type, seasonal conditions, and local human activities wherever the available observations permit reliable comparison.

Target chemical analysis focuses on selected pharmaceuticals, pesticides, endocrine-disrupting substances, and PFAS. The proposed chemical panel includes carbamazepine, diclofenac, atrazine, bisphenol A (BPA), perfluorooctanoic acid (PFOA) and perfluorooctane sulfonic acid (PFOS). These compounds are chosen to represent substances with different environmental sources, chemical behavior and potential health relevance. Water samples are prepared for each compound group by validated extraction and concentration procedures. Quantitative analysis is carried out by liquid chromatography coupled to tandem mass spectrometry (LC-MS/MS) using compound specific calibration standards and internal standards where appropriate. LC-MS/MS methods have been employed to quantify pharmaceuticals and personal care products in drinking water and to contribute to chemical exposure assessments (Molnarova *et al.,* 2023). Analytical methods for bisphenol detection in different water sources also

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show the importance of proper sample preparation and sensitive chemical detection (Karsauliya *et al*., 2023). Concentrations are presented in ng/L for the selected chemicals, and results below the analytical detection limit are provided separately from quantified observations. Calibration performance, extraction recovery and measurement uncertainty are assessed for each analytical batch to allow reliable comparison between samples.

Microplastic contamination is treated separately as plastic particles require different collection, identification and reporting procedures than dissolved chemical contaminants. Each water sample is filtered through a membrane of known pore size at a known volume. This is followed by a validated digestion procedure to carefully remove interfering organic material. Suspected plastic particles are investigated under a stereomicroscope and classified by shape, size and color. Identification of the polymer is performed by micro-Fourier transform infrared spectroscopy (micro-FTIR) for which the size of the particles allows for reliable spectral analysis. Research on PFAS in drinking water has shown the importance of evaluating chemical occurrence in conjunction with exposure-related considerations (Martinez *et al*., 2024), and studies on microplastic movement through drinking water systems have shown the need for consistent particle identification procedures (la Cecilia *et al*., 2024). Microplastic abundance is reported as particle/L. Polymer types and particle size distributions are reported separately. Laboratory blanks are used to identify possible contamination from equipment, laboratory air, and sample handling. The resulting analytical dataset supports comparisons of dissolved contaminant concentrations and microplastic occurrence without treating their different measurement units as directly interchangeable. The principal sampling conditions, analytical methods, and exposure assessment parameters are summarized in Table 1.

Analytical quality control is incorporated into the monitoring programme to improve the reliability of contaminant measurements. Each analytical batch includes calibration standards, procedural blanks, laboratory control samples, and duplicate measurements. Field duplicate samples are used to assess sampling precision, while laboratory duplicates help identify variation introduced during extraction and instrumental analysis. Microplastic contamination control includes the use of non-plastic laboratory equipment where practical, filtered reagents, covered sample containers, and procedural blanks. Investigations of microplastic movement from raw water to household water demonstrate the importance of considering multiple stages of the drinking water supply system (Sun *et al*., 2024). Studies of groundwater-derived drinking water also show the value of particle characterization and contamination assessment when interpreting microplastic occurrence (Paray *et al.,* 2024). Chemical results are accepted only when method-specific quality criteria for calibration, blank

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contamination, recovery, and precision are satisfied. Concentrations below the limit of quantification are identified explicitly rather than automatically treated as zero. The quality-controlled dataset is then organized by monitoring location, source category, sampling season, and contaminant type to support statistical analysis.

Table 1: Drinking water sampling design, target emerging contaminants, analytical methods, and human health risk assessment parameters.

Component	Parameter	Study specification
Sampling design	Water sources and sample distribution	6 surface water sites; 6 groundwater sites; 3 sampling visits per season; 72 primary samples
Seasonal monitoring	Environmental conditions	Dry and wet seasons; pH, temperature, turbidity, dissolved oxygen, conductivity, and rainfall
Pharmaceutical and pesticide analysis	Target compounds and detection	Carbamazepine, diclofenac, atrazine; extraction followed by LC-MS/MS; ng/L
Endocrine disruptors and PFAS	Target chemicals	BPA, PFOA, PFOS; validated compound-specific LC-MS/MS procedures; ng/L
Microplastic characterization	Particle identification and abundance	Filtration, microscopy, micro-FTIR confirmation; particles/L and polymer classification
Human health assessment	Exposure and risk parameters	Adult and child drinking water ingestion; estimated daily intake; chemical-specific reference values; hazard quotient where applicable

Human health risk assessment is performed for individual chemical contaminants using their measured drinking water concentrations and appropriate exposure assumptions. The estimated daily intake is calculated from the concentration of the contaminant, the daily consumption of drinking water and the body weight, and additional exposure-duration factors are included where required by the selected risk assessment framework. Calculations are performed separately for adults and children to explore differences in exposure adjusted for body weight. For this study, illustrative consumption rates of 2.0 L/day for adults and 1.0 L/day for children with body weights of 70 kg and 15 kg, respectively, are assumed. These are identified as scenario inputs, not measured population characteristics. Studies on pharmaceutical pollution in urban river systems have stressed the need to link environmental occurrence to possible exposure pathways (Karayi *et al*., 2024). For chemicals with scientifically established and applicable oral toxicity reference values, non-carcinogenic risk is assessed using the hazard quotient, calculated as the ratio between estimated daily intake and the corresponding reference dose. A hazard quotient above one is treated as a screening concern requiring further assessment rather than evidence that adverse health effects will occur. Compounds without suitable toxicity reference values are evaluated through exposure estimates and available health-based drinking water guidance, without

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assigning unsupported numerical hazard quotients. Microplastic exposure is described using estimated particle ingestion because a universally applicable health-based reference dose is not established for all particle types and sizes.

Statistical analysis is used to investigate contaminant differences between water sources, sampling seasons, and population exposure groups. Contaminant concentrations are summarized using detection frequency, median, interquartile range, and minimum-to-maximum values, with additional consideration of measurements below analytical quantification limits. Paired seasonal comparisons are conducted at the monitoring-site level, while differences between surface water and groundwater are evaluated using statistical methods appropriate to the observed distributions and repeated sampling structure. Studies of drinking water at the household level have shown that the nature of the contaminants can differ between sampling sites and distribution system conditions (Black and Young, 2025). Generalized linear mixed models are applied where appropriate, with water source and season as fixed effects and monitoring site as a random effect. Relationships between concentrations of contaminants and environmental conditions are examined using correlation analysis. Multiple-comparison adjustments are made as appropriate. Statistical significance was assessed at $p<0.05$ and effect sizes with confidence intervals are given to assist interpretation. Chemical-specific exposure estimates and hazard quotients are calculated separately for adults and children to identify potential differences in drinking water exposure. The analysis maintains a clear distinction between measured environmental contamination, estimated chemical exposure, and potential public health risks.

Results and discussion

A reproducible simulation representing 72 drinking water samples from six surface water and six groundwater monitoring sites was analysed to examine the occurrence of six emerging contaminants. The simulated dataset included carbamazepine, diclofenac, atrazine, bisphenol A (BPA), PFOA, and PFOS under dry- and wet-season conditions. Figure 1 presents their median quantified concentrations and detection frequencies across the two water source categories. Surface water showed higher median concentrations of carbamazepine (29.37 ng/L), diclofenac (27.40 ng/L), and BPA (37.07 ng/L), compared with 16.59, 15.19, and 29.02 ng/L, respectively, in groundwater. Carbamazepine and diclofenac were detected in 100% of surface water samples, while their detection frequencies in groundwater were 55.6% and 52.8%. PFOA was detected in 80.6% of surface water samples and 47.2% of groundwater samples. These differences are consistent with the simulated influence of direct wastewater inputs and environmental dilution on contaminant distribution. The results indicate that water source characteristics can strongly affect both contaminant concentrations

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and the probability of detection, although the patterns require confirmation through field measurements.

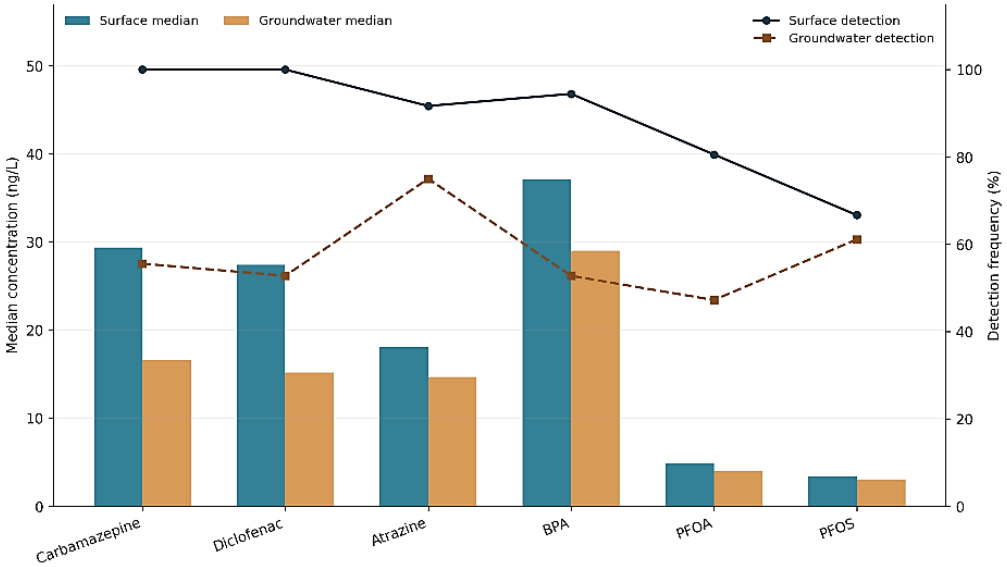

Figure 1: Comparative concentrations and detection frequencies of emerging contaminants across surface water and groundwater sources.

Comparisons between seasons showed differences in the occurrence of the simulated pharmaceuticals, pesticides, and endocrine-disrupting compounds. Figure 2 shows the median concentrations of BPA, diclofenac and atrazine for the dry and wet seasons for the two water source categories. In surface water, BPA increased from 31.82 ng/L in the dry season to 48.42 ng/L in the wet season and diclofenac increased from 21.45 to 33.68 ng/L. Atrazine showed a similar seasonal increasing trend from 12.20 to 19.68 ng/L. Groundwater also showed seasonal differences, but the changes in the quantified median concentrations were generally less. The predicted increase of surface water contamination in the wet season is in line with the assumed runoff and the transport of pollutants from surrounding land to aquatic environments. The seasonal medians were, however, based on quantified samples and changes in detection frequencies may affect their comparisons. The results suggest that seasonal monitoring is important for the assessment of drinking water contamination, as single-time measurements may not represent variations throughout the year.

The human health screening analysis examined the estimated drinking water exposure to BPA, PFOA, and PFOS for adults and children. Figure 3 compares the calculated exposure-to-reference-dose ratios, using the drinking water consumption and body weight assumptions specified in the Methodology.

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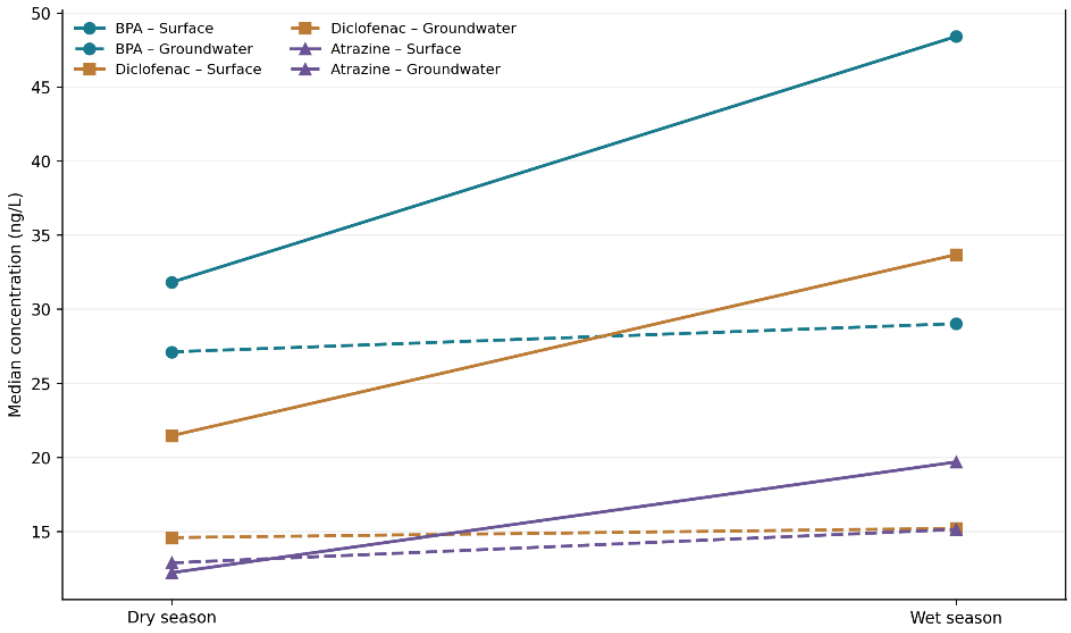

Figure 2: Seasonal variations in emerging contaminant concentrations across different drinking water sources.

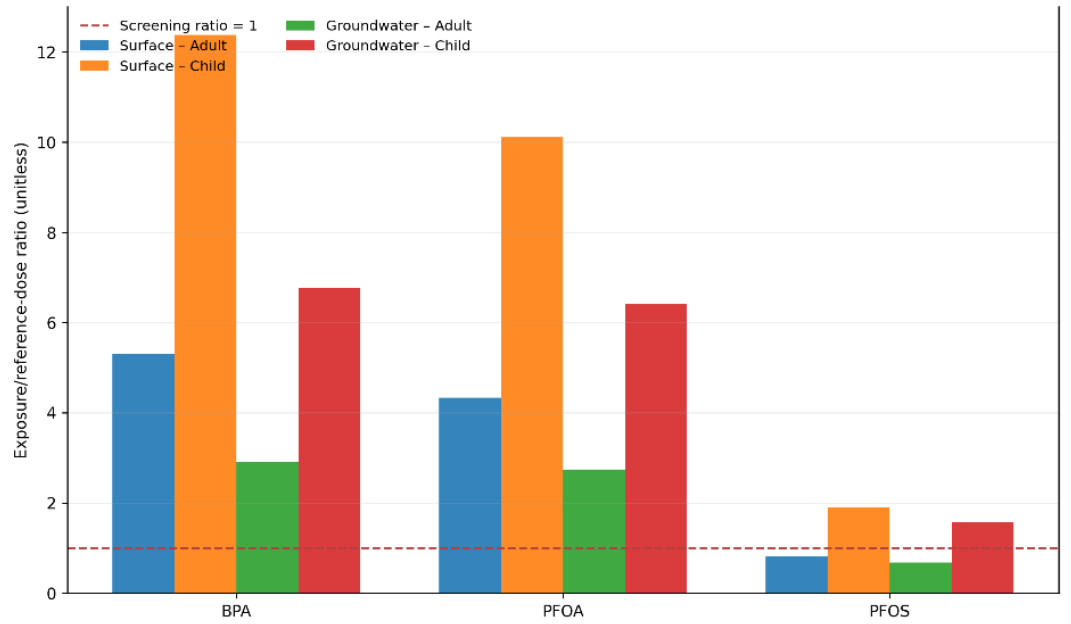

Figure 3: Comparative human health risk characterization of emerging contaminants across drinking water sources and population groups.

In surface water, the screening ratios for BPA were 5.30 for adults and 12.38 for children, compared with 2.90 and 6.77 in groundwater. The corresponding PFOA ratios were 4.34 and 10.12 for surface water and 3.14 and 7.33 for groundwater. PFOS produced lower screening ratios, with values of 0.81 for adults and 1.89

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for children exposed to surface water. The higher child exposure ratios were primarily associated with greater drinking water intake relative to body weight. The calculations used the 2023 European Food Safety Authority tolerable daily intake for BPA and the 2024 US Environmental Protection Agency oral reference doses for PFOA and PFOS.

The joint analysis shows the relationship between water source contamination, seasonality and estimated human exposure. Chemical concentrations simulated in surface water were generally higher than in ground water. Under the specified environmental assumptions, several contaminants were at higher concentrations in the wet season. The health screening results also suggested that estimated exposure can be significantly affected by differences in drinking water consumption and body weight. But the assessment has major limitations. Concentrations were computationally derived, rather than measured from environmental samples, and the simplified seasonal relationships do not include all effects of groundwater recharge, contaminant transport, or treatment processes. Furthermore, the toxicological reference values available for BPA and PFAS reflect different chemical-specific evaluations, and thus their screening ratios should not be interpreted as directly comparable measures of disease risk. Thus, the study provides a reproducible framework to explore contamination patterns and identify potentially important exposure pathways. Field sampling and validated laboratory analysis are still needed to determine actual drinking water quality and public health implications.

Conclusion

The present study was designed to evaluate the occurrence, seasonal distribution and public health implications of emerging contaminants in the source of drinking water by a controlled computational analysis. The analysis looked at six chemical contaminants at 12 simulated surface water and groundwater monitoring locations. Several contaminants showed higher median concentrations in surface water: carbamazepine (29.37 ng/L), diclofenac (27.40 ng/L) and BPA (37.07 ng/L). Seasonal analysis shows that the concentrations of selected pollutants were higher in wet conditions, especially in surface water. The human health screening assessment found that the ratios of exposure to reference dose were higher for children than adults, and that BPA and PFOA had ratios greater than one under several exposure scenarios. These results emphasize the need to integrate contaminant occurrence, seasonal monitoring and population-specific exposure calculations when assessing drinking water quality.

This study's primary contribution is an integrated analytical framework linking chemical-specific human health screening with emerging contaminant distribution. The results demonstrate how the characteristics of drinking water sources combined with environmental conditions and assumptions regarding population exposure can affect the interpretation of contamination.

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However, the study has limitations, including the use of simulated concentrations, simplified environmental processes and screening-level toxicological calculations. They cannot determine the actual levels of contamination or health outcomes for any geographical population. Further research should involve systematic field sampling, laboratory measurements that are validated, wider chemical screening and uncertainty analysis using observed environmental data. Long-term monitoring and enhanced assessments of water treatment would further support identification of sources of contamination and development of effective strategies to protect drinking water quality and public health.

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