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New organic groundwater pollutants in the national groundwater monitoring network of Poland

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Abstract
This article reports on emerging organic compounds (EOCs) discovered in groundwater samples collected within the national groundwater monitoring network of Poland. EOCs are very toxic substances that can significantly disrupt the functioning of living organisms. Monitoring of EOCs is not yet regulated within EU groundwater legislation, and so is rarely undertaken at national levels. In Poland EOCs are mainly monitored at local scales, usually undertaken by academic centres, except for the Polish Geological Institute – National Research Institute (PGI), which undertakes studies at broader scales, collecting samples from the national groundwater monitoring network. Data collected in 2016-2017 proved the presence of pharmaceutical substances in 53% of monitoring sites. Between 2022-2024 PGI continued sampling for pharmaceuticals, nonylophenol, 17-β-estradiol, PFAS, solvents and chelating agents. The results demonstrated the presence of EOCs in groundwater in Poland, especially in areas exposed to agriculture and industry, and in urban agglomerations. Pharmaceuticals have been found in 21%, PFAS compounds in 19% , nonylfenol in 17% and solvents and chelating substances in 45% of the boreholes sampled. Four substances were found sufficiently frequently to be placed on a list of substances to be regulated at EU level. These were carbamazepine, PFPeA, nonylfenol and 2-Ethoxy-2-methylpropane (ETBE).

Keywords: emerging organic contaminants, groundwater pollution, water quality, pharmaceuticals, PFAS, nonylophenol, PMT

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1. Introduction

Emerging organic compounds are synthetic or natural organic compounds such as pesticides, pharmaceuticals, oestrogens, surfactants, personal hygiene products, food additives and industrial additives, which are commonly used in many sectors of the economy and industry worldwide, and which enter the environment as a result of anthropogenic activities. They commonly pose a threat to the health and life of organisms by causing changes in the hormonal, immune, and endocrine systems and leading potentially to the development of serious illnesses. Research on the presence of EOCs in groundwater and their interactions and negative effects on living organisms has been conducted for several decades (Seiler et al., 1999; Sacher et al., 2001; Kolpin et al., 2002; Cordy et al., 2004; Verstraeten et al., 2005; Barnes et al., 2008; Zuccato et al., 2008; Loos et al., 2010; Vulliet and Cren-Olive, 2011, Stuart et al., 2012; Lapworth et al., 2012; de Jesus Gaffney et al., 2015) but it is the last decade that has provided the most information about their wide presence in groundwater (Bexfield et al., 2019; Bunting et al., 2021). This is linked to the development and improvement of analytical techniques capable of detecting small concentrations of EOCs. In Poland, monitoring of emerging contaminants in groundwater, despite overall good awareness of this problem worldwide, is still not included in the framework of the State Monitoring Programme. As such, funding is limited and the problem is addressed only in research projects. As reported by Ślósarczyk et al. (2021), only 14 scientific publications on the presence of pharmaceuticals and personal care products in Polish groundwater were available by 2021, the majority of which had limited spatial extent, being focused on local problems. Since then, four more publications appeared, and these were also focused on local problems such as landfill leachate (Ślósarczyk and Dąbrowska, 2025), drinking water quality (Sikora et al., 2025, Ślósarczyk et al., 2025) and general characterisation of urban groundwater in the Kraków area (Rusianiak et al., 2021). Most of the Polish publications on emerging contaminants report studies of pharmaceuticals and personal care products (Caban et al., 2015; Kapelewska et al., 2016; Kuczyńska, 2017, 2019; Kuczyńska and Janica, 2017; Kruć et al., 2019a,b, 2022, 2023; Szymczycha et al., 2020; Kmiecik et al., 2020; Rusiniak et al., 2021; Ślósarczyk and Dąbrowska, 2025; Ślósarczyk

et al., 2025). Studies on other groups of emerging contaminants, such as industrial chemicals including PMT (persistent, mobile and toxic) and PFAS (per- and polyfluorinated) substances are still very few (Kapelewska et al., 2016; Kapelewska et al., 2018; Sikora et al., 2025).
This article reports the results of pilot monitoring studies focused on a total of 72 emerging contaminants analysed by the Polish Geological Institute – National Research Institute (PGI) between 2022 -2024, as a follow up of EOCs studies carried out by PGI in 2016-2017 (Kuczyńska, 2019). This included 11 pharmaceutical active substances, 16 PFAS compounds, nonylophenol, 17-β estradiol, and 43 solvents and chelating agents. Samples were taken from monitoring boreholes included in the national groundwater monitoring network. As such, despite the pilot character of the research, the results provide more nationwide cover than the other studies so far reported from Poland.

1.1 Properties of EOCs included in the review

Pharmaceuticals are chemical substances that are biologically active and used in human and veterinary medicine. High production and consumption of drugs is recognised as a global problem, causing pharmaceuticals and their metabolites to pollute the environment, including groundwater (Kuczyńska, 2017). Per- and polyfluoroalkyl substances (PFAS) are a large class of thousands of synthetic chemicals that are used throughout society. Their global use started in the 1940s and led to environmental pollution that is linked to negative effects on human health. Due to carbon-fluorine bonds being one of the strongest chemical bonds in organic chemistry, PFAS are resistant to degradation processes. For that reason they are often called “forever chemicals”. Most PFAS are also easily transported over long distances in the environment. Nonylphenol (NP) is an anionic surfactant, a substance similar to detergents with a wide range of applications, leading to their common presence in the environment. Nonylphenol is produced in large quantities and is used in both industrial processes and in consumer laundry detergents, personal hygiene products, products containing polyvinyl chloride (PVC), automotive applications, in latex paints, epoxy and phenolic resins, and in lawn care products and pesticides (Lacorte et al., 2002, Soares et al., 2008). Nonylphenol is highly toxic to aquatic organisms. It can accumulate in tissues and leads to the feminization of aquatic organisms, reducing male fertility, and impacts the viability of young individuals. 17-ß estradiol (E2) is a natural oestrogen that is known to cause endocrine-disturbing effects, being toxic to aquatic ecosystems and dangerous for human health (Scheer, 2022). Specifically it has been associated with increased rates of breast and prostate cancer, decreased sperm quality, premature menopause and virilization in young girls. Estradiol is widely used for oral contraception and in post-menopausal hormonal therapy. Solvents and chelating agents are synthetic organic chemicals of common use in many fields of industry. Due to their intrinsic properties, such as persistence, mobility and toxicity they are very dangerous to the environment and to human health. They can travel long distances and stay in the environment bounded to soil, which makes them a long-lasting threat to drinking water resources (Hale et.al., 2020).

2. Materials and methods

Data reported in this article were gathered within three separate sampling campaigns, for which separate research objectives and funding were set, hence the number of sampling locations and the number of analysed parameters in every campaign were different. Some campaigns included more than one group of chemicals.

2.1 Analytes

The selection of pharmaceutical and PFAS compounds analysed in 2022 was based on recommendations given by the CIS Working Group Groundwater in 2019 (CIS, 2019a,b) and reflected parameters considered in the selection of candidates for either inclusion in the voluntary groundwater watch list or in regulations under the Groundwater Directive. This included the following substances (Table 1): pharmaceuticals: sulfadiazine, erythromycin, clatromicin, clopidol, crotamiton, primidone, sotalol, ibuprofen, diatrozoic acid, sulfametoxazole and carbamazepine; PFAS compounds: perluorobutanoic acid (PFBA), 4:2 monoPAP, perfluoropentanoic acid (PFPeA), perfluorohexamoic acid (PFHxA), perfluorobutane sulfonic acid (PFBS), 6:2 monoPAP, perfluoroheptanoic acid (PFHpA), perfluorodecylphosphonic acid (PFDPA), perfluorooctanoic acid (PFOA), perfluorohexane sulfonic acid (PFHxS), perfluorononanoic acid (PFNA), perfluorooctylphosphoric acid (PFOPA), perfluorodecanoic acid (PFDA), perfluorooctane sulfonic acid (PFOS), perfluoroundecanoic acid (PFUnA) and perfluorododecanoic acid ((PFDoA). According to analysis done by the CIS Working Group Groundwater these pharmaceuticals and PFAS compounds either frequently occur in groundwater or have large potential to be present in groundwater across the EU and therefore require further monitoring (CIS, 2019a,b). Nonylophenol and 17-β estradiol were chosen for the study in 2023 because of concerns over their endoctrine-disrupting properties, which was addressed in Drinking Water Regulation 2020/2184. The group of 43 solvents and chelating agents surveyed in 2024 was selected following a methodology used by experts of the CIS Working Group Groundwater, who selected them from a group of PMT (permanent, mobile, toxic) substances as defined by the German Federal Environmental Agency (Neuman and Schliebner, 2019) for the purpose of selecting candidates for either inclusion in the voluntary groundwater watch list or in regulations under the Groundwater Directive. The list of substances included: 1,1,1-Trichlorethane, 1,1,2,2-Tetrachlorethane, 1,1,2-Trichlorethane, 1,1-Dichlorethylene, 1,1-Dichloroethane, 1,2,3-Trichlorbenzene, 1,2,4-Trichlorbenzene, 1,2,4-Trimethylbenzene, 1,2-Dichlorobenzene, 1,2-Dichloroethane, 1,2-dichloropropane, 1,3,5-Trimethylbenzene, 1,4-Dioxane, 2-Ethoxy-2-methylpropane, benzene, bromdichlormethane, carbon tetrachloride, chlorobenzene, chloroethane, chloroform, chloromethane, cis-1,2-Dichloroethene, dibromochlormethane, dichloromethane, diethylene glycol dimethyl ether, diisopropylether, EDTA, ethylbenzene, isopropylbenzene, n-butylbenzene, n-nropylbenzene, NTA, tert-butanol, tert-butyl methyl ether, tetrachloroethene, tetraglyme, tetrahydrofuran, toluene, trans-1,2-Dichloroethene, tribromomethane, trichloroethene, trifluoroacetic acid and vinyl chloride.

Table 1. Characteristics of chemicals and analytical methods described in the article

No.	Parameter	Group	CAS number	Analytical method	Limit of Quantification [µg/L]
1	Diatrozioic acid	pharmaceutical	117-96-4	LC-MS/MS SPE	0.023
2	Sotalol	pharmaceutical	3930-20-9	LC-MS/MS SPE	0.015
3	Sulfadiazine	pharmaceutical	68-35-9	LC-MS/MS SPE	0.014
4	Clopidol	pharmaceutical	2971-90-6	LC-MS/MS SPE	0.017
5	Primidone	pharmaceutical	125-33-7	LC-MS/MS SPE	0.012
6	Sulfametoxazole	pharmaceutical	723-46-6	LC-MS/MS SPE	0.013
7	Carbamazepine	pharmaceutical	298-46-4	LC-MS/MS SPE	0.011
8	Erythromycin	pharmaceutical	114-07-8	LC-MS/MS SPE	0.013
9	Clarithromycin	pharmaceutical	81103-11-9	LC-MS/MS SPE	0.014
10	Crotamiton	pharmaceutical	483-63-6	LC-MS/MS SPE	0.014
11	Ibuprofen	pharmaceutical	15687-27-1	LC-MS/MS SPE	0.024
12	PFBA	PFAS	375-22-4	LC-MS/MS SPE	0.006
13	4:2 monoPAP	PFAS	150065-76-2	LC-MS/MS SPE	0.026
14	PFPeA	PFAS	2706-90-3	LC-MS/MS SPE	0.020
15	PFHxA	PFAS	307-24-4	LC-MS/MS SPE	0.019
16	PFBS	PFAS	375-73-5	LC-MS/MS SPE	0.011
17	6:2 monoPAP	PFAS	57678-01-0	LC-MS/MS SPE	0.028
18	PFHpA	PFAS	375-85-9	LC-MS/MS SPE	0.013
19	PFDPA	PFAS	52299-26-0	LC-MS/MS SPE	0.016
20	PFOA	PFAS	335-67-1	LC-MS/MS SPE	0.013
21	PFHxS	PFAS	355-46-4	LC-MS/MS SPE	0.016
22	PFNA	PFAS	375-95-1	LC-MS/MS SPE	0.012
23	PFOPA	PFAS	40143-78-0	LC-MS/MS SPE	0.031
24	PFDA	PFAS	335-76-2	LC-MS/MS SPE	0.011
25	PFOS	PFAS	1763-23-1	LC-MS/MS SPE	0.017
26	PFUnA	PFAS	2058-94-8	LC-MS/MS SPE	0.012
27	PFDoA	PFAS	307-55-1	LC-MS/MS SPE	0.011
28	17-β estradiol	endoctrine disturbant	50-28-2	LC-MS/MS SPE	0.3
29	4-nonylphenol	endoctrine disturbant	84852-15-3	LC-MS/MS SPE	0.1
30	1.1.1-Trichlorethane	solvent and chelating agents	71-55-6	HS-GC-MS	0.25
31	1.1.2.2-Tetrachlorethane	solvent and chelating agents	79-34-5	HS-GC-MS	0.25
32	1.1.2-Trichlorethane	solvent and chelating agents	79-00-5	HS-GC-MS	0.25
33	1.1-Dichlorethylene	solvent and chelating agents	75-35-4	HS-GC-MS	0.25

No.	Parameter	Group	CAS number	Analytical method	Limit of Quantification [µg/L]
34	1.1-Dichloroethane	solvent and chelating agents	75-34-3	HS-GC-MS	0.25
35	1.2.3-Trichlorbenzene	solvent and chelating agents	87-61-6	HS-GC-MS	0.25
36	1.2.4-Trichlorbenzene	solvent and chelating agents	120-82-1	HS-GC-MS	0.25
37	1.2.4-Trimethylbenzene	solvent and chelating agents	95-63-6	HS-GC-MS	0.25
38	1.2-Dichlorobenzene	solvent and chelating agents	95-50-1	HS-GC-MS	0.25
39	1.2-Dichloroethane	solvent and chelating agents	107-06-2	HS-GC-MS	0.25
40	1.2-dichloropropane	solvent and chelating agents	78-87-5	HS-GC-MS	0.25
41	1.3.5-Trimethylbenzene	solvent and chelating agents	108-70-3	HS-GC-MS	0.25
42	1.4-Dioxane	solvent and chelating agents	123-91-1	GC-MS/MS	0.5
43	2-Ethoxy-2-methylpropane	solvent and chelating agents	637-92-3	HS-GC-MS	0.02
44	Benzene	solvent and chelating agents	71-43-2	HS-GC-MS	0.25
45	Bromdichlormethane	solvent and chelating agents	75-27-4	HS-GC-MS	0.25
46	Carbon tetrachloride	solvent and chelating agents	56-23-5	HS-GC-MS	0.25
47	Chlorobenzene	solvent and chelating agents	108-90-7	HS-GC-MS	0.25
48	Chloroethane	solvent and chelating agents	75-00-3	HS-GC-MS	0.25
49	Chloroform	solvent and chelating agents	67-66-3	HS-GC-MS	0.25
50	Chloromethane	solvent and chelating agents	74-87-3	HS-GC-MS	0.25
51	cis-1.2-Dichloroethene	solvent and chelating agents	156-59-2	HS-GC-MS	0.25
52	Dibromochlormethane	solvent and chelating agents	124-48-1	HS-GC-MS	0.25
53	Dichloromethane	solvent and chelating agents	75-09-2	HS-GC-MS	0.25
54	Diethylene glycol dimethyl ether	solvent and chelating agents	111-96-6	GC-MS/MS	1
55	Diisopropylether	solvent and chelating agents	108-20-3	HS-GC-MS	2
56	EDTA	solvent and chelating agents	60-00-4	LC-UV	1
57	Ethylbenzene	solvent and chelating agents	100-41-4	HS-GC-MS	0.25
58	Isopropylbenzene	solvent and chelating agents	98-82-8	HS-GC-MS	0.25
59	n-Butylbenzene	solvent and chelating agents	104-51-8	HS-GC-MS	0.25
60	n-Propylbenzene	solvent and chelating agents	103-65-1	HS-GC-MS	0.25
61	NTA	solvent and chelating agents	139-13-9	LC-UV	1
62	Tert-butanol	solvent and chelating agents	75-65-0	HS-GC-MS	2
63	Tert-butyl methyl ether	solvent and chelating agents	1634-04-4	HS-GC-MS	0.5
64	Tetrachloroethene	solvent and chelating agents	127-18-4	HS-GC-MS	0.25

No.	Parameter	Group	CAS number	Analytical method	Limit of Quantification [µg/L]
65	Tetraglyme	solvent and chelating agents	143-24-8	LC-MS/MS	0.03
66	Tetrahydrofuran	solvent and chelating agents	109-99-9	HS-GC-MS	0.05
67	Toluene	solvent and chelating agents	108-88-3	HS-GC-MS	0.25
68	trans-1.2-Dichloroethene	solvent and chelating agents	156-60-5	HS-GC-MS	0.25
69	Tribromomethane	solvent and chelating agents	75-25-2	HS-GC-MS	0.25
70	Trichloroethene	solvent and chelating agents	79-01-6	HS-GC-MS	0.25
71	Trifluoroacetic Acid	solvent and chelating agents	76-05-1	LC-MS/MS	10
72	Vinylchlorid	solvent and chelating agents	75-01-4	HS-GC-MS	0.25
LC-MS/MS – Liquid Chromatography coupled with Tandem Mass Spectrometry LC-MS/MS SPE – Liquid Chromatography coupled with Tandem Mass Spectrometry and Solid Phase Extraction HS-GC-MS – Headspace Gas Chromatography-Mass Spectrometry GC-MS/MS – Gas Chromatography-Mass Spectrometry LC-UV – Liquid Chromatography-Ultraviolet					

2.2. Sampling locations

Locations selected for groundwater sampling were chosen from the points belonging to the national groundwater monitoring network used for WFD water quality monitoring and located throughout the entire country. To optimise resources for the research, sampling was done in parallel to the operational monitoring. For that reason the majority of sampling sites were located within GWBs identified to be at risk of not achieving environmental objectives, which is either in GWBs being of poor status or where pressures threatening the status were identified. Sampling points were analysed in terms of location and the construction of the borehole, following the criteria: a. shallow occurrence of the monitored aquifer with no or a limited confining layer; b. location within or in close proximity to urban agglomerations or unsewered rural areas; c. location at short distances from documented contamination sources such as cemeteries, hospitals, sewage treatment plants; or, at short distances from surface water courses. Samples were taken in a total of 268 locations situated within 96 GWBs. Pharmaceuticals and PFAS compounds were surveyed in 106 monitoring points that were located within an area of 63 groundwater bodies (GWBs). Nonylfenol and 17-β estradiol were surveyed in 151 monitoring boreholes spread within 72 GWBs and solvents and chelating agents were studied in 56 monitoring boreholes located within 29 GWBs. Monitoring boreholes were mostly screened in porous deposits (over 90% of monitoring points) of Quaternary age (75%). Depth to the aquifer varied from o to 240 m b.g.l; however in 75% monitoring boreholes did not exceed 25 m b.g.l. Characteristics and locations of water sampling locations are provided in Figure 1 and Supplementary data_Table 1, respectively.

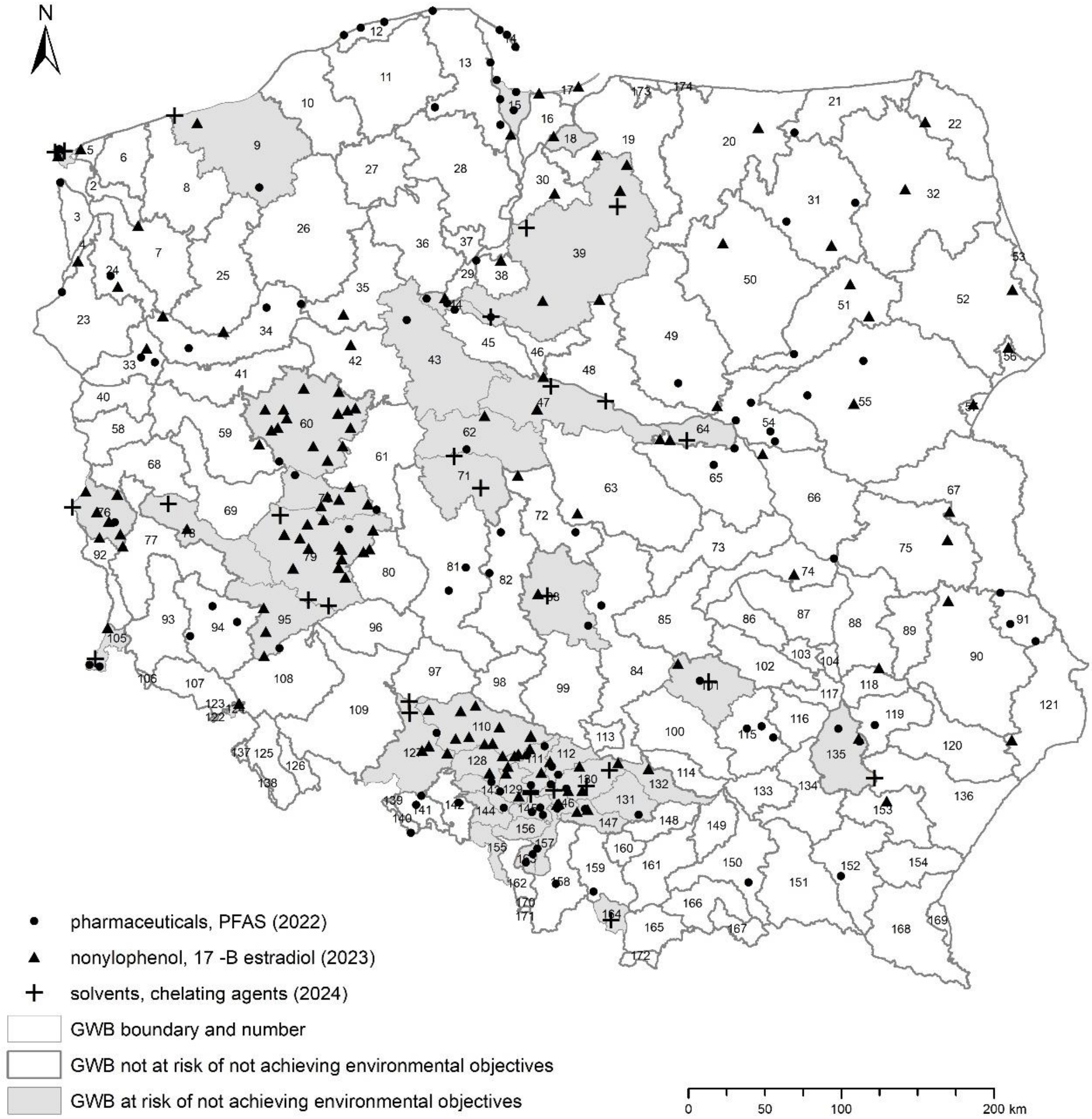

Figure 1. Sampling locations

2.3. Sampling procedures and transportation

To collect representative groundwater samples, the wells from which water samples were taken were previously pumped using portable pumping sets, suction pumps, or Gigant or Gigant & While type pumps. During the pumping, measurements of the stabilization of the following parameters were made: temperature, pH level, and electrolytic conductivity (EC), which aimed to establish inflow of fresh water from the aquifer to the well. Depending on the stability of the substances monitored, the volume of water pumped from the wells ranged from 3 to 5 times the volume of stagnant water. Samples were collected according to “clean hands-dirty hands” protocol. Water samples for pharmaceuticals, nonylophenol, 17-β estradiol and PMT substances were collected into dark brown glass bottles (40-1000 ml volume), samples for PFAS were collected into HDPE bottles of 1000 ml volume. Depending on the analyte, samples were conditioned with HCl, Na_2SO_4 or H_2SO_4. The sampling team was asked not to use any pharmaceuticals, sunscreen or other personal care products on the day of sampling. Samples were delivered to analytical laboratories packed in coolboxes within 24 hours from sampling.

2.4 Analytical procedures

Water samples for pharmaceuticals, PFAS, nonylfenol and 17-β estradiol were analysed in the Chemical Laboratory of the Polish Geological Institute using the LC-MS/MS method with SPE extraction. Samples for solvents and chelating agents were analysed in an external, commercial laboratory and the analytical methods used included LC-MS/MS, LC-UV, HS-GC-MS and LC-MS/MS.

Limits of quantification for every analyte were defined based on information gathered in reports from CIS Working Group Groundwater, which collected a large amount of data on analytical methods during the voluntary groundwater watch list process (CIS, 2019a, 2024). For nonylfenol and 17-β estradiol the limits of quantification were defined to fulfill recommendations of the Drinking Water Directive 2000/2184 (Polish version). In the Polish version of the directive, recommended guidance values for nonylfenol and 17-β estradiol were 0.3µg/l and 1µg/l and therefore LOQ levels for these substances were defined at 0.1µg/l and 0.3µg/l. It was later discovered that in the original, English text of the directive, the guidance value for 17-β estradiol was 1 ng/l and therefore the LOQ value for the study was too high to detect it. Parameters of analytical methods used in this study are given in Table 1.

3. Results

The research on pharmaceuticals carried out between 2022-2024 showed the presence of their active substances in 22 out of 106 monitoring boreholes, which is 21% of the samples. 7 out of 11 pharmaceuticals included in the study were found: these were diatrozoic acid, sotalol, clopidol, primidone, sulfametoxazole, carbamazepine and ibuprofen. The pharmaceutical that was most often found was carbamazepine, which was recorded in 10 locations (9% of sampling locations). The second most often found was sulfametoxazole, recorded at 4 locations (4% of sampled sites). Other pharmaceuticals were found in 1 or 2 monitoring boreholes only. With respect to concentrations, these were generally low. The highest concentration of an active substance was carbamazepine, found at 0.23 µg/l (Table 2).

Out of 16 per- and polyfuoralkyl substance selected for the study, 8 were identified in samples collected in 2022. These were PFPeA, PFBS, 6:2 monoPAP, PFDPA, PFOA, PFHxS, PFOPA and PFUnA. The substance most often found was PFPeA, which is used in production of grease and waterproof packaging, carpets and furniture textiles. It was found at 15 locations (14% of all samples). Other PFAS compounds were found in 1–3 locations. In total PFAS compounds were located in 20 monitoring boreholes (19% of all sampling locations). With respect to concentrations, the highest, at 0.12 µg/l, was found for PFPeA. The remaining analytes were found at levels of <0.01–0.03 µg/l (Table 2).

Nonylfenol and 17-β estradiol were surveyed in 151 monitoring boreholes. Nonylfenol was found at 25 sampling locations, which constitutes 17% of all sites. 17-ß-estradiol was not found in any of sampling points included in the study, most likely due to the too high LOQ. Concentrations of nonylfenol in the groundwater samples varied from 0.14 to 0.93 µg/l, table 2.

The last study of solvents and chelating agents revealed their presence at 25 out of 56 sampling locations, which constitutes 45% of all points included in the study. 14 chemicals from this group were found and these included 2-Ethoxy-2-methylpropane (ETBE), benzene and carbon tetrachloride, chloroform, cis 1,2-Dichloroethene, dibromochloromethane, dichloromethane, EDTA, ethylobenzene, NTA, tetraglyme, toluene, tribromomethane and trichloroethene. 2-Ethoxy-2-methylpropane (ETBE) was the most often found chemical (11 out of 56 sampling locations, 20% of samples). ETBE is an additive to petroleum products. Its highest concentration was at 0.17 µg/l. Toluene, which is a solvent used in many industries including paint production, cosmetics (nail polish), pharmaceutical and military products, was found in 8 locations (14% of samples) and its highest concentration was at 2.5 µg/l. TFA, a commonly used organic acid often found in groundwater, was not detected in this research, probably due to a too high LOQ level.

Table 2. Maximum concentrations of analytes included in the study

Analyte	LOQ [µg/l]	No of samples collected	No of samples with results > LOQ	Maximum concentration [µg/l]
Diatrozoic acid	0.05	100	1	0.05
Sotalol	0.01	106	1	0.01
Clopidol	0.01	106	2	0.02
Primidone	0.01	106	2	0.03
Sulfametoxazole	0.01	106	4	0.01
Carbamazepine	0.01	106	10	0.01
Ibuprofen	0.05	106	2	0.09
PFPeA	0.01	106	15	0.01
PFBS	0.01	106	2	0.01
6:2 monoPAP	0.01	106	3	0.01

Analyte	LOQ [µg/l]	No of samples collected	No of samples with results > LOQ	Maximum concentration [µg/l]
PFDPA	0.01	106	2	
PFOA	0.01	106	1	0.03
PFHxS	0.01	106	1	0.02
PFOPA	0.01	106	1	0.01
PFUnA	0.01	106	1	0.01
nonylfenol	0.1	151	25	0.93
2-Ethoxy-2-methylpropane (ETBE)	0.02	56	12	0.17
Benzene	0.25	56	3	0.4
Carbon tetrachloride	0.25	56	1	2.1
Chloroform	0.25	56	1	13
cis 1,2-Dichloroethene	0.25	56	3	1.2
Dibromochloromethane	0.25	56	1	6
Dichloromethane	0.25	56	1	1.7
EDTA	1	56	5	6
Ethylobenzene	0.25	56	5	0.43
NTA	1	56	3	3
Tetraglyme	0.03	56	1	0.13
Toluene	0.25	56	8	2.5
Tribromomethane	0.25	56	1	1.1
Trichloroethene	0.25	56	1	1.1

In total, emerging organic contaminants were found in 69 out of 268 sampling points (26%) in which the depth to the aquifer varied from 0 to 69.7 m b.g.l. 87% of these boreholes were screened in porous, Quaternary deposits. Only 9 represented fissured aquifers. At over 90% of these points, depth to an aquifer was <20 m and in 45% <5 m depth. The water table was phreatic in 71%, which shows that the most vulnerable aquifers are shallow and unconfined.

4. Discussion

The research was directed towards delivering information on the presence of selected emerging contaminants in groundwater in Poland. The results reported here follow previous pilot studies undertaken within the national groundwater monitoring network (Kuczyńska, 2017) and corroborate the presence of emerging contaminants in groundwater in Poland.

Return of samples with positive results of emerging contaminants was relatively high, though sampling was undertaken at a limited number of places. The selection of monitoring sites was aimed at places where impact from anthropogenic pressures was anticipated and where hydrogeological conditions would facilitate their occurrence. It is expected that returns would be lower if more monitoring boreholes were included in the study and if they were spread more evenly across the country. Since sampling was done at selected sites, drawing conclusions about the correlation of relationships with the conditions of occurrence seems unjustified and could differ if the number of points covered by the studies were larger.

Nonetheless, according to the methodology of the CIS WG Groundwater strategy (CIS, 2019b) for selection of chemicals to be recommended for consideration of inclusion into the Groundwater Directive regulation, the number of sites with a positive result per country was defined at 10 per substance. Occurrence of a substance in 10 sites in at least 4 EU countries makes a substance fulfil the criteria of so-called List Facilitating (LF), which includes substances considered to be of high concern for groundwater quality at EU level and as such to be regulated at European level. Based on the pilot studies reported in this article, 4 substances meet these criteria, which are carbamazepine, PFPeA, nonylfenol and 2-Ethoxy-2-methylpropane (ETBE). Carbamazepine, PFPeA and ETBE are already included in LF based on information gathered from other EU countries (CIS, 2019b, 2024). Nonylfenol has not been analysed by the CIS Groundwater WG.

The other factor limiting positive results in this study could be the limits of quantification. Chemicals covered in this research are generally expected to occur in low concentrations, hence analytical methods with low limits of quantifications are needed to detect them. Lower limits of quantification are often associated with increased uncertainty of results. For that reason the analytical methods and their limits of quantification should be chosen with respect to required guidance values. Unfortunately, the majority of substances covered in this research are not yet regulated under EU and national regulations. Lack of regulations defining acceptable levels of concentrations of these substances makes it difficult to decide what limit of quantification is required, even for a pilot study. Despite efforts taken to assure the best LOQ for the study, it is still possible that for some substances the limits of quantifications were set too high, including 17-β estradiol and TFA.

5. Conclusion

This article presents previously unpublished results of concentrations of emerging contaminants in groundwater in Poland, confirming their presence in groundwater within the national groundwater monitoring network. The presence of a wide range of different groups of chemicals indicates the necessity of carrying further investigations and scientific research, especially with respect to chemicals that are not regulated in national and international legislations, but are already documented to be harmful to the environment and to have intrinsic properties allowing them to travel across large distances and to bioaccumulate in the subsoil environment. The presence of these substances may be harmful not only to humans and animals via drinking contaminated water, but also to microfauna living underground (stygofauna), which influence microbiological processes taking place in the groundwater environment. These results demonstrate further that regulations of emerging contaminants in groundwater are urgently needed as well as regular monitoring of these compounds in groundwater. One shall also expect that when regulations are in place this will impact upon our perception of groundwater quality and groundwater status across Poland and EU, which will result in a need to develop new strategies towards the protection of groundwater.

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References

Barnes, K., Koplin, D., Furlong, E., Zaugg, S., Meyer, M., Barber, L., 2008. A national reconnaissance of pharmaceuticals and other organic wastewater contaminants in the United States – I) Groundwater. Science of The Total Environment, **402**: 192–200, https://doi.org/10.1016/j.scitotenv.2008.04.028

Bexfield, L.M., Toccalino, P.L., Belitz, K., Foreman, W.T., Furlong, E.T., 2019. Hormones and pharmaceuticals in groundwater used as a source of drinking water across the Unites States. Environmental Science & Technology, **53**: 2950-2960, https://doi.org/10.1021/acs.est.8b05592

Bunting, S.Y., Lapworth, D.J., Crane E.J., Groma-Olmedo, J., Koroša, A., Kuczyńska, A., Mali, N., Rosenqvist, L., Van Vliet, M.E., Togola, A., Lopez, B., 2021. Emerging organic compounds in European groundwater. Environmental Pollution, **269**, 115945, https://doi.org/10.1016/j.envpol.2020.115945

Caban, M., Lis, E., Kumirska, J., Stepnowski, P., 2015. Determination of pharmaceutical residues in drinking water in Poland using a new SPE-GC-MS (SIM) method based on Speedisk extraction disks and DIMETRIS derivatization. Science of The Total Environment, **538**: 402–411, https://doi.org/10.1016/j.scitotenv.2015.08.076

CIS - Common Implementation Strategy For The Water Framework Directive And The Floods Directive, 2019a. List facilitating Annex I and II review process of the GWD. https://circabc.europa.eu/ui/group/9ab5926d-bed4-4322-9aa7-9964bbe8312d/library/e00af115-e106-4be5-8b0f-ff210c3df737?p=1&n=10&sort=modified_DESC

CIS - Common Implementation Strategy For The Water Framework Directive And The Floods Directive, 2019b. Voluntary Groundwater Watch List V. 3.2. https://circabc.europa.eu/ui/group/9ab5926d-bed4-4322-9aa7-9964bbe8312d/library/e00af115-e106-4be5-8b0f-ff210c3df737?p=1&n=10&sort=modified_DESC

Cordy, G.E., Duran, N.L., Bouwer, H., Rice, R.C., Furlong, E.T., Zaugg, S.D., Meyer, M.T., Barber, L.B., Kolpin, D.W., 2004. Do Pharmaceuticals, Pathogens, and Other Organic Waste Water

Compounds Persist When Waste Water Is Used for Recharge? Groundwater Monitoring & Remediation, **24**: 58-69, https://doi.org/10.1111/j.1745-6592.2004.tb00713.x
de Jesus Gaffney, V., Almeida, C.M., Rodrigues, A., Ferreira, E., Benoliel, M.J., Cardoso, V.V., 2015. Occurrence of pharmaceuticals in a water supply system and related human health risk assessment. Water Research, **72**: 199-208, https://doi.org/10.1016/j.watres.2014.10.027
Hale, S., Arp, H.P., Schliebner, I., Neumann, M., 2020. What's in a Name: Persistent, Mobile, and Toxic (PMT) and Very Persistent and Very Mobile (vPvM) Substances. Environmental Science & Technology, **54**: 14790-14792, https://doi.org/10.1021/acs.est.0c05257
Kapelewska, J., Kotowska, U., Wiśniewska, K., 2016. Determination of personal care products and hormones in leachate and groundwater from Polish MSW landfills by ultrasound-assisted emulsification microextraction and GC-MS. Environmental Science and Pollution Research, **23**: 1642-1652, https://doi.org/10.1007/s11356-015-5359-9
Kapelewska, J., Kotowska, U., Karpińska, J., Kowalczuk, D., Arciszewska, A., Świrydo, A., 2018. Occurrence, removal, mass loading and Environmental risk assessment of emerging organic contaminants in leachates, groundwaters and wastewaters. Microchemical Journal, **137**: 292-301, https://doi.org/10.1016/j.microc.2017.11.008
Kmiecik, E., Styszko, K., Wątor, K., Dwornik, M., Tomaszewska, B., 2020. BPA – an endocrine disrupting compound in water used for drinking purposes, a snapshot from South Poland. Geology, Geophysics & Environment, **46**: 5-16, https://doi.org/10.7494/geol.2020.46.1.5
Kolpin, D., Furlong, E., Meyer, M., Thurman, E., Zaugg, S., Barber, L., Buxton, H., 2002. Pharmaceuticals, hormones, and other organic wastewater contaminants in U.S. streams, 1999–2000: Methods, development and national reconnaissance. Environmental Science and Technology, **36**: 1202–1211, https://doi.org/10.1021/es011055j
Kruć-Fijałkowska, R., Dragon, K., 2022. Factors affecting the concentrations of pharmaceutical compounds in river and groundwaters: efficiency of river bank filtration (Mosina-Krajkowo well field, Poland). Geological Quarterly, **66**, 3, http://dx.doi.org/10.7306/gq.1635
Kruć-Fijałkowska, R., Dragon, K., Górski, J., 2019a. Pharmaceuticals in river and bank filtrate water in Krajkowo (Poland) (in Polish with English summary). Biuletyn Państwowego Instytutu Geologicznego, **475**: 109-116, https://doi.org/10.7306/bpig.13
Kruć-Fijałkowska, R., Dragon, K., Górski, J., 2019b. Migration of pharmaceuticals from the Warta River to the aquifer at a riverbank filtration site in Krajkowo (Poland). Water, **11**, 2238, https://doi.org/10.3390/w11112238
Kruć-Fijałkowska, R., Drożdżyński, D., Matusiak, M., Dragon, K., 2023. Dependence of the pharmaceutical concentrations in the Warta River water (Poland) on successive waves of COVID-19 pandemic. Research Square, https://doi.org/10.21203/rs.3.rs-3470616/v1
Kuczyńska, A., 2017. Results of a pilot study on the assessment of pharmaceuticals in groundwater in samples collected from the national groundwater monitoring network (in Polish with English summary). Przegląd Geologiczny, **65**: 1096-1103.
Kuczyńska, A., 2019. Presence of pharmaceutical compounds in groundwater with respect to land use in the vicinity of sampling sites. Geologos, **25**: 231-240, https://doi.org/10.2478/logos-2019-0025
Kuczyńska, A., Janica, R., 2017. Analysis of the influence of sewage from diffuse sources on the groundwater quality, exemplified by research results of the Polish Hydrogeological Survey intervention team (in Polish with English summary). Przegląd Geologiczny, **65**: 1312-1318.
Lacorte, S., Latorre, A., Guillamon, M., Barcelo, D., 2002. Nonylphenol, Octyphenol, and Bisphenol A in groundwater as a Result of Agronomic Practices. The Scientific World Journal, **2**: 1095-1100, https://doi.org/10.1100/tsw.2002.219
Lapworth, D.J., Baran, N., Stuart, M.E., Ward, R.S., 2012. Emerging organic contaminants in groundwater: A review of sources, fate and occurrence. Environmental Pollution, **163**: 287–303, https://doi.org/10.1016/j.envpol.2011.12.034
Loos, R., Locoro, G., Comero, S., Contini, S., Schwesig, D., Werres, F., Balsaa, P., Gans, O., Weiss, S., Blaha, L., Bolchi, M., Gawlik, B.M., 2010. Pan-European survey on the occurrence of selected polar organic persistent pollutants in ground water. Water Research, **44**: 4115–4126, https://doi.org/10.1016/j.watres.2010.05.032
Neuman, M., Schliebner, I., 2019. Protecting the sources of our drinking water: The criteria for identifying persistent, mobile and toxic (PMT) substances and very persistent and very mobile (vPvM) substances under EU Regulation REACH (EC) No 1907/200. https://www.umweltbundesamt.de/en/publikationen/protecting-the-sources-of-our-drinking-water-the
Rusiniak, P., Kmiecik, E., Wątor, K., Duda, R., 2021. Pharmaceuticals and personal care products in the urban groundwater – preliminary monitoring (case study: Kraków, Southern Poland). Urban Water Journal, **18**: 364-374. https://doi.org/10.1080/1573062X.2021.1893354

Sacher, F., Lange, F., Brauch, H.J., Blankenhorn, I., 2001. Pharmaceuticals in groundwaters. Analytical methods and results of a monitoring program in Baden–Württemberg, Germany. Journal of Chromatography A., **938**: 199–210. https://doi.org/10.1016/S0021-9673(01)01266-3
SCHEER (Scientific Committee on Health, Environmental and Emerging Risks), 2022. Scientific Opinion on "Draft Environmental Quality Standards for Priority Substances under the Water Framework Directive", 17-alpha-ethinylestradiol (EE2), Beta-Estradiol (E2) and Estrone (E1). https://health.ec.europa.eu/publications/scientific-opinion-draft-environmental-quality-standards-priority-substances-under-wfd-17-alpha_en
Seiler, R.L., Zaugg, S.D., Thomas, J.M., Howcroft, D.L., 1999. Caffeine and pharmaceuticals as indicators of waste-water contamination in wells. Ground Water, **37**: 405–410. https://doi.org/10.1111/j.1745-6584.1999.tb01118.x
Sikora, D., Poniedziałek, B., Rzymski, P., 2025. Assessment of PFAS levels in drinking water: A case study from Poznań County (Poland). Chemosphere, **377**, 144326 https://doi.org/10.1016/j.chemosphere.2025.144326
Soares, A., Guieysse, B., Jefferson, B., Cartmell, E., Lester, J.N., 2008. Nonylphenol in the environment: A critical review on occurrence, fate, toxicity and treatment in wastewaters. Environment International, **34**: 1033–1049. https://doi.org/10.1016/j.envint.2008.01.004
Stuart, M., Lapworth, D., Crane, E., Hart, A., 2012. Review of risk from potential emerging contaminants in UK groundwater. Science of The Total Environment, **416**: 1–21. https://doi.org/10.1016/j.scitotenv.2011.11.072
Szymczycha, B., Borecka, M., Białk-Bielińska, A., Siedlewicz, G., Pazdro, K., 2020. Submarine groundwater discharge as a source of pharmaceutical and caffeine residues in coastal ecosystem: Bay of Puck, southern Baltic Sea case study. Science of The Total Environment, **713**, 136522. https://doi.org/10.1016/j.scitotenv.2020.136522
Ślósarczyk, K., Dąbrowska, D., 2025. A closed municipal landfill as a source of emerging contaminants in adjacent groundwater: pharmaceuticals and personal care products occurrence and environmental risk assessment. Journal of Hydrology, **654**, 132829. https://doi.org/10.1016/j.jhydrol.2025.132829
Ślósarczyk, K., Jakóbczyk-Karpierz, S., Różkowski, J., Witkowski, A.J., 2021. Occurence of pharmaceuticals and personal care products in the water environment of Poland: A review. Water, **13**, 2283. https://doi.org/10.3390/w13162283
Ślósarczyk, K., Wolny, F., Witkowski, A., 2025. Monitoring of pharmaceuticals and personal care products to assess water quality changes and pollution sources in a drinking water reservoir catchment. Water Resources and Industry, **33**, 100283. https://doi.org/10.1016/j.wri.2025.100283
Verstraeten, I.M., Fetterman, G.S., Meyer, M.T., Bullen, T., Sebree, S.K., 2005. Use of Tracers and Isotopes to Evaluate Vulnerability of Water in Domestic Wells to Septic Waste. Ground Water Monitoring & Remediation, **25**: 107–117. https://doi.org/10.1111/j.1745-6592.2005.0015.x
Vulliet, E., Cren-Olive, C., 2011 Screening of pharmaceuticals and hormones at the regional scale, in surface and groundwaters intended to human consumption. Environmental Pollution, **159**: 29–34. https://doi.org/10.1016/j.envpol.2011.04.033
Zuccato, S., Castiglioni, S., Bagnati, R., Chiabrando, C., Grassi, P., Fanelli, R., 2008. Illicit drugs, a novel group of environmental contaminants. Water Resources, **42**: 961–968. https://doi.org/10.1016/j.watres.2007.09.010