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Small springs in a big city: Status, stressors, and long-term changes of their water properties across Warsaw

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Abstract: The present study attempted to identify the current status and stressors affecting spring water properties in an urban area, using the example of the Warsaw agglomeration. For this purpose, they study monitored hydrological and hydrochemical properties of three springs, each draining a Quaternary porous aquifer and representing different anthropopressure across the city. The measurements of discharge and physico-chemical parameters were carried out regularly twice a month from June 2023 to May 2024, while the chemical composition, including main cations and anions, was determined once every two-month period using ion chromatography. The results documented a good agreement between the degree and timing of impact of human-induced alternations and the physico-chemical properties of spring waters. The highest total dissolved solids (*TDS*) and concentrations of Cl^-, SO_4^{2-}, and Na^+ were measured in the most urbanised areas. Seasonal changes in the spring water chemistry, primarily in terms of main anions, confirmed their anthropogenic origin, related to different deposition and migration over time. A comparison with archival data proved significant long-term transformation of spring properties, including gradual decrease of their discharge, increase in water temperature, and changes to the hydrochemical type. Such an evolution of groundwater quality reflects the impact of climate warming and human activities, including increase in the degree of imperviousness as a result of urbanisation, application of road maintenance chemicals, and emission of pollution to the atmosphere. The results provide the most recent insight on shallow groundwater status and stressors in Warsaw and reflect intensive modification of the aquifer system across the urban environment.

Keywords: anthropopressure, chemical composition, groundwater, springs, stressors, urbanisation

INTRODUCTION

Springs play a unique role in the environment, exhibiting significant differences in their form, location in relation to the relief of the land, physical and chemical properties of water, and discharge. This diversity allows them to perform various functions, which sometimes may overlap and interact (Kresic, 2010; Upreti, Kayastha and Bhuiyan, 2024). As geogenic factors, such as duration of water circulation within the soil-rock matrix, type of the dominant minerals, as well as properties of the aquifer system, usually play a dominant role in physico-chemical regime of groundwater (Baba and Gündüz, 2017; Zhang *et al.*, 2019), springs in rural and urbanised areas could serve as indicators of changes within the aquifer system driven by several anthropogenic stressors (Barquin and Scarsbrook, 2008; Siwek and Pociask-Karteczka, 2017). Such a diagnostic role is particularly valuable in the context of changes in the environment, such as climate change and urban sprawl (Chauhana *et al.*, 2023), and could help in the appropriate management of such areas (Caro-Borrero *et al.*, 2024).

Previous investigations of springs have focused mainly on the spatial and temporal variability of water chemistry, as well as evaluation of discharge patterns and water temperature regimes (Gaglioti *et al.*, 2019). The studies could help identify stressors, inducing changes in spring discharge, transformation of their thermal regime, and pollution of groundwater horizon (Chauhana *et al.*, 2023). In contrast to mountainous and foothill areas, similar studies have not been broadly conducted in lowland areas, mainly due to scarcity of spring outflows and their lower discharge rates (Siepak, Lewandowska and Sojka, 2023). Although spring water properties have been investigated in some regions of northern and central Poland, such as Białystok (Jekatierynczuk-Rudczyk *et al.*, 2022), Łódź (Moniewski, 2004), Lubuska Upland (Szczucińska, 2016), and Western Pomerania (Mazurek, 2008), they mainly concentrated on the rural or mixed, semi-natural landscapes. Thus, the presence of springs within the Warsaw metropolitan area provides a unique possibility to use them as tracers of human activity across a large city. It is worth noting that the study of spring water properties in Warsaw has a long historical record: water temperature was measured in the nineteenth century (Pusz, 1844), while the chemical composition was determined by Pich and Płochniewski (1968) in the 1960s. The most complete and comprehensive characterisation of Warsaw spring waters was presented by Kużawa and Gutry-Korycka (2002). With the exception of the UW N spring, investigated recently by Krogulec *et al.* (2022), no systematic monitoring of Warsaw's springs has been conducted for nearly twenty years, despite the presence of a numerous stressors that could potentially affect the quantity and quality of groundwater (Dziedziczak, 2006). Thus, the understanding of the current impact of the Warsaw agglomeration on spring water characteristics remain insufficient.

The main goal of this study was to identify the current status and key stressors influencing spring water properties in an urban area, using the Warsaw agglomeration as a case study. This could be achieved by implementing specific objectives to evaluate the spatio-temporal variability of physico-chemical properties of spring waters in different parts of the city (1), as well as to identify the long-term transformations in selected water properties in the past 60 years (2).

STUDY MATERIALS AND METHODS

STUDY AREA

The three springs, located across the Warsaw metropolitan area, belong to the Warsaw Escarpment, considered to be one of the most prominent landforms in the city (Fig. 1). It serves as a border between two other dominant geomorphological landforms, the Vistula Valley and the glacial upland (Dziedziczak, 2006), formed by pre-Quaternary and Quaternary sediments. The older upland sediments are composed of Pliocene silts, with local impurities of sand and clay; they serve as an impermeable bed for the Quaternary deposits (Kużawa and Gutry-Korycka, 2002). The Quaternary layer comprises gravel, sand, mule, clay, and varved silts. Sediments across the upland are characterised by glacial deformations, with many cracks, which serve as pathways for groundwater circulation. Due to lithological and geological structure of the bedrock, two main infiltration-fed aquifers exist across the glacial upland. The depth of the first one ranges from several meters to a dozen meters and is characterised by an unconfined groundwater table. The one residing deeper (at several dozen meters) is confined or semi-confined; both aquifers are hydraulically connected. The shallowest aquifer resides within the Quaternary sediments, which naturally have higher permeability, and as a result, provides weaker isolation for the groundwater.

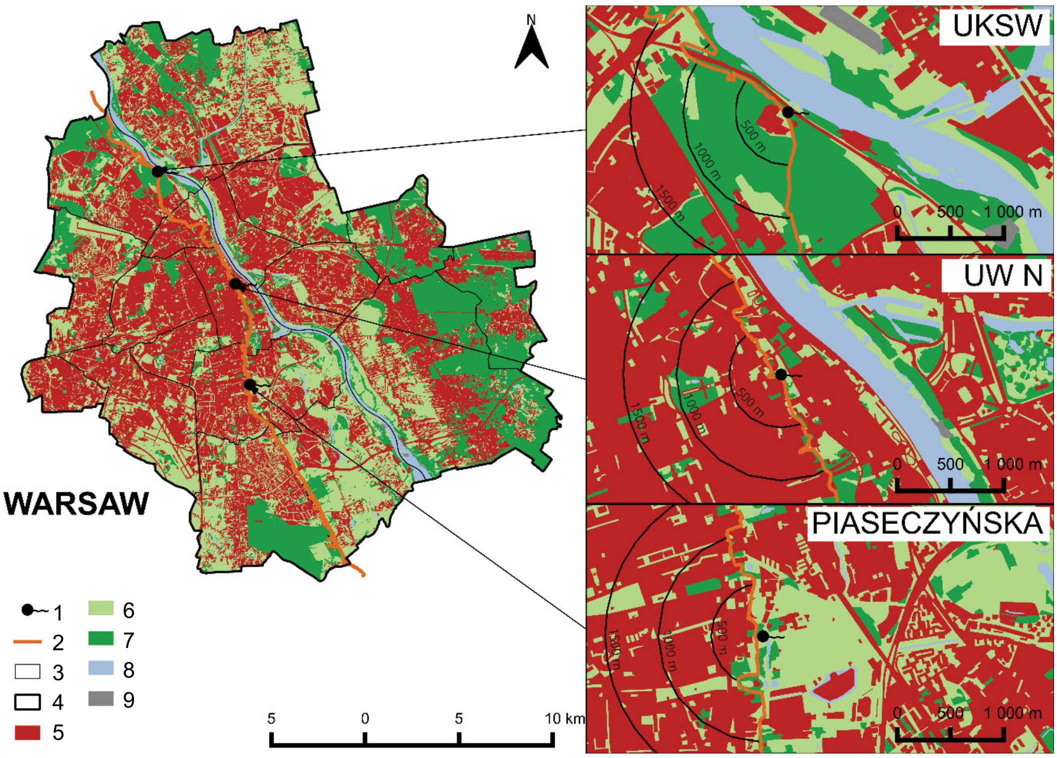


Fig. 1. Localisation of the investigated springs and their recharge areas and the Warsaw land cover; *1* – springs, *2* – Warsaw escarpment, *3* – district borders, *4* – Warsaw borders, *5* – urbanised areas, *6* – low vegetation, *7* – forested areas, *8* – surface waters, *9* – undeveloped land; source: own elaboration based on data from Topographic Objects Database (BDOT10k) (geoportal, no date)

The climate of the Warsaw metropolitan area can be described as humid continental (Peel, Finlayson and McMahon, 2007). According to Tomczyk and Bednorz (2022), the average annual air temperature in Warsaw in 1991–2020 was 8.5°C, while the annual precipitation sum for the same period totalled approximately 550 mm. Due to the presence of an urban heat island, the air temperature varies between different parts of the city, with higher values in the city centre and lower on its outskirts. Precipitation patterns also exhibit variability across different parts of the city, with the lowest totals noted in the northwestern part of the city and increasing towards the southwest.

METHODS

Three descending, perennial springs (Photo 1), located in different parts of the city, were selected for year-long monitoring of their hydrological and hydrochemical properties from June 2023 to May 2024. The UKSW spring, located in the northern part of the city, receives recharge from the Bielański Forest Nature Reserve, an old deciduous forest populated mainly by oaks, common hornbeams, maples, and alders. The spring outflow is located within a small university campus. The UW N spring is located in the inner centre of the city, draining an aquifer beneath the historical city centre. This area is characterised by a high degree of imperviousness, intensive traffic, and high modification of shallow geological structure, including deep basements and remains of historical urban infrastructure. The southernmost Piaseczyńska spring is located below the Mokotów residential and service district, a modern urban area characterised by residential and commercial development, including office and apartment buildings. According to Pich and Płochniewski (1968), the UW N spring is fed from sands of Riss glaciation origin, making such an aquifer particularly vulnerable to pollutant migration due to weak isolation. In contrast, the UKSW and Piaseczyńska springs drain from a deeper aquifer, laying directly over the Pliocene loams and the oldest glacial clays.

Twice a month (on the beginning and in the half of the month), the basic physico-chemical properties of spring water, including temperature, specific electrical conductivity (*SEC*), and pH, were measured with the Hanna HI98129 multimeter. The multimeter was regularly calibrated in reference buffers to ensure accuracy of 0.5°C for temperature, ±2% of full scale for *SEC*, and 0.05 for pH. The same sampling intervals were approved for discharge, using the volumetric method. Every two months, chemical composition of spring waters was determined, to capture variation under different hydrometeorological conditions (July, September, November, January, March, May). Thus, water samples were collected in 100 ml polyethylene test-tubes and immediately transported to the laboratory at 4°C. Concentrations of macroelements (Ca^{2+}, Mg^{2+}, K^+, Na^+, SO_4^{2-}, Cl^-, F^-) and biogenic compounds (PO_4^{3-}, NO_3^-, NO_2^-, NH_4^+) were determined using a Metrohm ion chromatograph. The concentration of HCO_3^- was analysed separately via the acidimetric titration method using HCl (0.1 N) and methyl orange as an indicator. To verify the accuracy of the chemical analysis, the ion balance method was applied. The difference between the total concentrations of anions and cations did not exceed 5%, indicating that the results fell within the acceptable range of the analytical error.

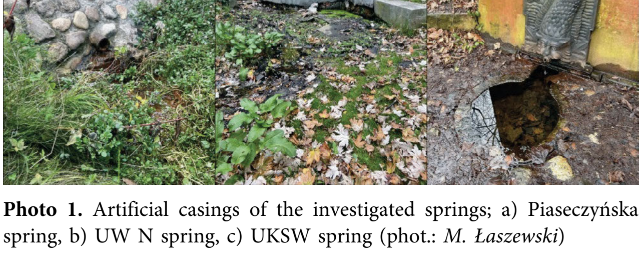


Photo 1. Artificial casings of the investigated springs; a) Piaseczyńska spring, b) UW N spring, c) UKSW spring (phot.: *M. Łaszewski*)

To assess the spatial variability of discharge, water temperature, *SEC*, and pH, basic statistical parameters were calculated for whole year measured time series, including mean, maximum, minimum, and standard deviation. Results were presented on box-whiskers charts. In addition, the Maillet coefficient of discharge irregularity (Q_{max}/Q_{min}) (Bartnik and Moniewski, 2019) was computed. The hydrochemical type of spring waters was determined using the Szczukariew-Prikłonski synthetic classification, commonly applied in Poland (Macioszczyk, 1987). The spatio-temporal variability of water chemistry was presented on Schoeller diagram.

RESULTS

SPATIAL VARIABILITY OF DISCHARGE AND PHYSICO-CHEMICAL PROPERTIES

The studied springs exhibited clear spatial variability in both discharge and basic physico-chemical properties (Fig. 2). Discharge values varied from 0.3 $dm^3 \cdot min^{-1}$ in the UKSW spring to 2.6 $dm^3 \cdot min^{-1}$ in the Piaseczyńska spring. The Maillet coefficient of variability was differentiated from 2.0 in UKSW and 2.4 in Piaseczyńska springs to 2.8 in UW N spring, indicating a stable discharge regime across the sites. The mean annual water temperature was generally similar and varied from 11.0 to 11.4°C. However, as indicated by standard deviation of water temperature, the UW spring exhibited the greatest seasonal variability, while the UKSW was the most thermally stable. Among the measured parameters, the specific electrical conductivity showed the greatest spatial differentiation. The UKSW spring recorded the lowest *SEC* at 930 $\mu S \cdot cm^{-1}$, while the UW N spring the highest value at 2875 $\mu S \cdot cm^{-1}$. Similarly to water temperature, the UW N spring was again the most unstable, with standard deviation of 58 $\mu S \cdot cm^{-1}$. Regarding pH, UW N spring was the most acidic, while the UKSW and Piaseczyńska springs showed slightly alkaline conditions.

The chemical composition of the investigated spring waters also exhibited clear spatial variability (Tab. 1). Total dissolved solids (*TDS*) of spring waters ranged, on average, from 709 $mg \cdot dm^{-3}$ in the UKSW spring to 1961 $mg \cdot dm^{-3}$ in the UW N spring (Tab. 1). In all studied spring waters, Ca^{2+} was the dominant cation; its contribution was clearly higher in the UKSW spring (on average 62.7% $mval \cdot dm^{-3}$), whereas in the UW N spring, it fell below 50% $mval \cdot dm^{-3}$. The contribution of Na^+ and Mg^{2+} was also significant, with Na^+ reaching up to 35.1% $mval \cdot dm^{-3}$ in the UW N spring. These cations were generally wider distributed than Mg^{2+}. The contribution of K^+ ions varied notably, ranging from just 0.66% $mval \cdot dm^{-3}$ in the Piaseczyńska

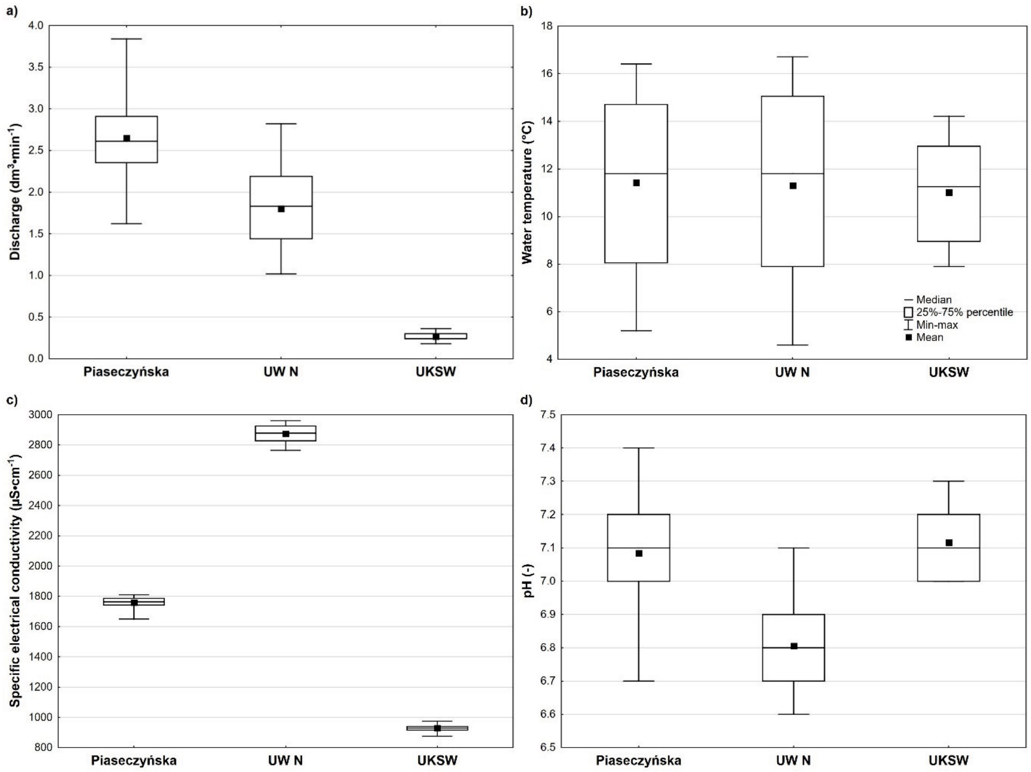


Fig. 2. Distribution of measured values of: a) spring discharge, b) water temperature, c) specific electrical conductivity, d) pH in the three investigated springs in the period from June 2023 to May 2024; source: own study

spring to 6.4% mval·dm^{-3} in the UKSW spring. Definitely higher variability was observed across springs in terms of the major anions. In the UKSW spring, HCO_3^- was a dominant anion, contributing 53.4% mval·dm^{-3}, followed Cl^- and SO_4^{2-} ions at 17.8% and 17.3% mval·dm^{-3}, respectively. In contrast, in the Piaseczyńska and UW N springs, Cl^- ions were the most abundant (48.5% and 45.9% mval·dm^{-3}). In the UW N spring, SO_4^{2-} was the second most dominant anion, while in the Piaseczyńska spring, it was HCO_3^-. Substantial concentrations of NO_3^- ions were also detected, with the highest levels found in the UKSW spring, reaching up to 15.7% mval·dm^{-3}. According to the Szczukariew-Prikłoński hydrochemical classification, the UKSW spring exhibited a simple, two-ionic HCO_3-Ca type, while the Piaseczyńska and UW N springs were characterised by complex, five-ionic types Cl-HCO_3-SO_4-Ca-Na and Cl-SO_4-HCO_3-Ca-Na, respectively.

Table 1. Mean, maximum, and minimum concentrations (mg·dm^{-3}) of ions and total dissolved solids (*TDS*) in the three investigated springs in the period from June 2023 to May 2024

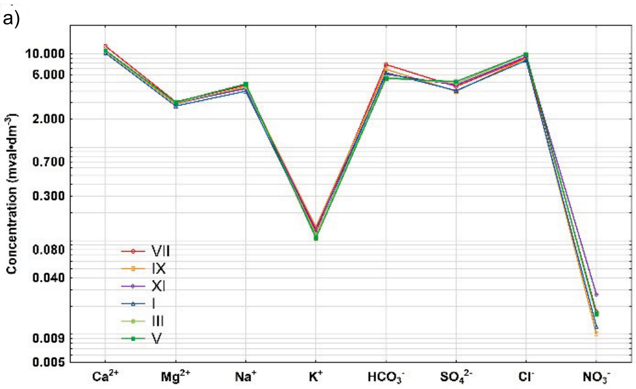
Ion	Piaseczyńska spring		UW N spring		UKSW spring	
	range	mean	range	mean	range	mean
Ca^{2+}	203.8–242.3	218.5	270.4–299.5	284.6	114.3–132.2	119.3
Mg^{2+}	33.6–37.3	35.9	42.8–46.1	44.6	16.4–17.8	16.9
Na^+	91.7–109.3	101.3	232.1–242.8	237.7	30.9–35.7	34.2
K+	4.2–5.5	4.8	40.5–47.9	44.2	20.9–28.0	23.7
NH_4^+	0.07–0.16	0.12	0.15–0.39	0.25	0.03–0.20	0.12
HCO_3^-	333.6–469.5	386.5	348.2–461.7	406.6	270.1–359.1	309.5
SO_4^{2-}	190.8–242.7	216.2	373.6–474.8	408.9	70.6–84.4	78.7
Cl^-	301.4–351.6	328.2	474.8–552.0	516.4	53.8–66.7	59.8
F^-	0.4–1.52	0.83	0.36–0.77	0.59	0.23–0.61	0.38
NO_3^-	0.6–1.7	1.0	12.5–19.5	15.1	19.6–90.8	65.4
NO_2^-	0.05–0.08	0.07	0.0–0.12	0.08	0.0–0.03	0.01
PO_4^{3-}	0.0–0.06	0.01	0.27–1.14	0.45	0.17–0.49	0.40
TDS	1217–1400	1295	1887–2051	1961	679–783	709

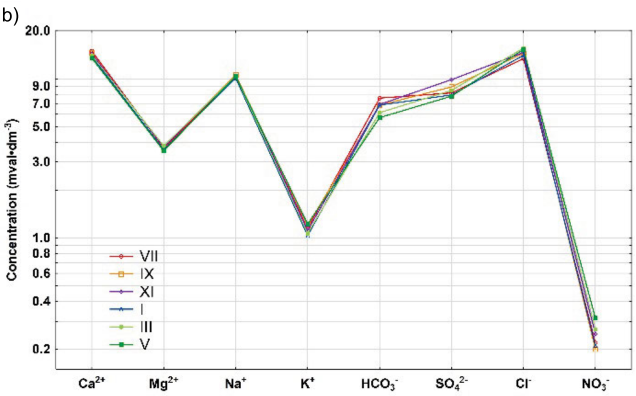
Source: own study.

SEASONAL AND LONG-TERM CHANGES OF HYDROCHEMICAL PROPERTIES

The chemical composition of spring waters exhibited temporal variability across the investigated period; however, it was different depending on the spring and ion type (Fig. 3). Generally, the concentrations of cations showed small differences, with only minor fluctuations (Fig. 3). In contrast, anions such as Cl^-, HCO_3^-, NO_3^-, and SO_4^{2-}, exhibited marked seasonal variability in the studied period. Notably, Cl^- concentrations in the Piaseczyńska and UW N springs were relatively higher during the spring months, such as March and May, in comparison to summer and autumn (Fig. 3). In the UW N spring, this seasonal increase resulted in the Cl^- contribution to the total anion balance in the UW N spring ranging from 45.6% (474.8 mg·dm^{-3}) to 52.5% mval·dm^{-3} (542.5 mg·dm^{-3}). The same trend was noted for NO_3^- ions in the UW N and UKSW springs. In the latter, the contribution of nitrates ranged from 3.4% (19.6 mg·dm^{-3}) to even 15.7% mval·dm^{-3} (90.8 mg·dm^{-3}) (Fig. 3). In contrast, there was no clear seasonal pattern across the investigated springs for SO_4^{2-} concentration. In the Piaseczyńska spring, the highest concentrations of SO_4^{2-} were recorded during spring, while in the UW N spring, the peak concentration was measured in autumn. Interestingly, the contribution of HCO_3^- generally showed a negative correlation with the Cl^- and SO_4^{2-} concentrations. The increase in their concentrations and contribution during spring resulted in the simultaneous decrease in HCO_3^- (Fig. 3).

A comparison between the current hydrological and hydrochemical conditions of the springs with archival data from the 20th century highlights long-term transformations of spring water properties (Tab. 2). Overall, the discharge of all springs has decreased since the 1990s, with the most pronounced reduction observed in the UKSW spring, where mean values were 14 times lower between 1990s and 2024. While a similar decline in discharge was also evident in the Piaseczyńska and UW N springs, such reductions were not observed between the 1960s and the 1990s. In contrast, water temperature in all springs increased





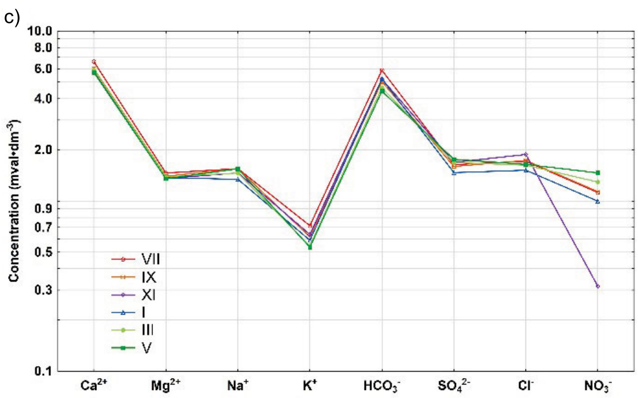


Fig. 3. Concentrations of major cations and anions in certain seasons in the waters of: a) Piaseczyńska, b) UW N, c) UKSW springs; source: own study

Table 2. Changes of spring water properties based on current study and previous research

Spring	Piaseczyńska			UW N			UKSW		
	Q	*T*	HT	*Q*	*T*	HT	*Q*	*T*	HT
1964–1966 (Pich and Płochniewski, 1968)	8.0–9.0 / –	6.0–10.5 / –	HCO_3-SO_4-Cl-Ca-Na	0.9–1.7 / 1.3	–	SO_4-HCO_3-Cl-Ca-Na	– / 4.0	–	HCO_3-SO_4-Ca-Na
VII 1995–VI 1996 (Kużawa and Gutry-Korycka, 2003)	9.4–19.6 / 16.0	6.2–13.4 / 10	–	1.3–4.9 / 3.0	5.7–12.1 / 10.6	–	3.5–4.9 / 4.2	6.7–10.9 / 9.0	–
2003 (Dziedziczak, 2006)	–	–	HCO_3-SO_4-Cl-Ca	–	–	SO_4-Cl-HCO_3-Ca-Na	–	–	SO_4-Ca-Na-Mg
2023–2024 current study	1.6–3.8 / 2.6	5.2–16.4 / 11.4	Cl-HCO_3-SO_4-Ca-Na	1.0–2.8 / 1.8	4.6–16.7 / 11.3	Cl-SO_4-HCO_3-Ca-Na	0.18–0.36 / 0.3	7.9–14.2 / 11.0	HCO_3-Ca

Note: for discharge and water temperature – minimum and maximum values above the line, and average values below the line.
Explanations: *Q* = discharge (dm^3·min^{-1}), *T* = water temperature (°C), HT = hydrochemical type, "–" = no data; source: own elaboration, Pich and Płochniewski (1968), Kużawa and Gutry-Korycka (2002), and Dziedziczak (2006).

since the 1990s, both in terms of mean and maximum values. Notably, in the UW N spring, a gradual increase in temperature has been observed since the 1960s, with maximum values reaching 5.9°C (Tab. 2). The hydrochemical types of spring waters have exhibited significant evolution since the 1960s, with these transformations displaying spatial variability (Tab. 2). Major transformation could be observed in the Piaseczyńska spring, where the contribution of Cl^- ions initially declined from the 1960s to the early 2000s, but has recently increased, making Cl^- the dominant anion in the current chemical composition. In contrast, between 1968 and 2003, the hydrochemical type of the UW N spring did not change significantly. However, in 2024, a significant shift was noted, with Cl^- concentrations exceeding those of both SO_4^{2-} and HCO_3^-. The UKSW spring exhibited a different pattern of transformation from a four-ionic composition to a quasi-natural HCO_3-Ca hydrochemical type (Tab. 2).

DISCUSSION

The present study assessed the current status and stressors affecting spring waters in an urbanised environment, using the Warsaw metropolitan area as a case study. This objective was achieved by evaluating the spatio-temporal variability of physico-chemical spring water properties, as well as by tracking their long-term changes. The results documented a strong correlation between the degree and duration of anthropopressure and the observed physico-chemical properties of spring waters. The intensive human activity in the historical parts of Warsaw over 350 years of its development (Bernatowicz, 2022) was reflected in the increased total dissolved solids (*TDS*) and concentrations of ions in the UW N spring water. In fact, the recharge area of the UW N spring in the Śródmieście district represents the most transformed part of the city, influenced by both contemporary and historical pollution sources. Present-day stressors include road traffic, leakage from sewage system, atmospheric deposition, and lawn fertilisation, while past impacts result from former waste dumpsites, pit latrines, and ruins of buildings, especially those destroyed during World War II. A similar set of stressors, though with a shorter duration of influence, shapes the chemical composition of Piaseczyńska spring. The recharge area of this spring lies within the Mokotów district, which, even after 1945, retained a dispersed and often rural character. Intensive urbanisation of this part of the city only started in the 1960s and continues to this day. This mosaic of alternations primarily increases concentrations of SO_4^{2-}, Cl^-, Na^+, and K^+, commonly recognised as indicators of human activity impact (Krogulec *et al.*, 2022). Importantly, elevated levels of such ions in the two springs were found to be several times higher than those typically recorded in other lowland, quasi-natural Quaternary outflows in post-glacial areas in Poland (Jekatierynczuk-Rudczyk *et al.*, 2022; Siepak, Lewandowska and Sojka, 2023), and even compared to springs in other geographical regions (Juodkazis and Papievis, 2007). The UKSW spring exhibited the most quasi-natural chemical composition, characterised by a HCO_3-Ca hydrochemical water type, which is typical for Quaternary sediment post-glacial aquifers (Nowicki and Sadurski, 2010). However, despite this general geochemical profile, the UKSW spring also showed high contamination with NO_3^-, reaching levels similar to those observed in agricultural areas polluted by fertilisers (Siwek, 2012; Łaszewski *et al.*, 2024). This nitrate contamination appears to result from a combination of factors. In this context, periodical release of nutrients from organic matter decomposition in forests (Foster, Nicolson and Hazlett, 1989), together with the destruction of their undergrowth by recreational activities, as well as additional artificial eutrophication of the recharge area by atmospheric deposition from Accelor-Mittal ironwork and the Żerań coal-fuelled power plant should be considered. The presence of various threats to groundwater chemistry was also reflected by observed temporal changes of the chemical composition. Although the *TDS* are generally influenced by spring discharge through dilution effects (Mostowik *et al.*, 2021), in the current study, this relationship appeared negligible due to the relatively stable drainage of the porous aquifer, as indicated by Maillet coefficients. Thus, the observed increases in the migration of anions, such as Cl^-, SO_4^{2-}, NO_3^- and the Na^+ cations, are more likely linked to their elevated seasonal deposition within the urban environment. In particular, the application of road maintenance substances during winter, combined with intensive traffic and winter emission to the atmosphere with a negative impact on the quality of air and precipitation (Sówka *et al.*, 2019) serve as an additional and simultaneously seasonal source of ions entering the groundwater system (Uliasz-Misiak *et al.*, 2022). It must be emphasised that increased seasonal anionic variability, apart from higher deposition in the urban environment, could be related to their easier migration through porous, Quaternary sediments (clay-rich fractions) due to their lower sorption affinity to mineral surfaces (Havlin, 2013).

The pressure on groundwater across the urban environment was also evidenced by identifying long-term transformation of selected water properties in the past 60 years. Overall, there was a significant decrease of discharge in all investigated springs, which was particularly evident from the 1990s to the present; the increase of the discharge between the 1960s and 1990s in the UW N spring was likely the result of underestimation by Pich and Płochniewski (1968), possibly due to differences in measurement location. The observed trend of declining discharge could be attributed to the combined interaction of several factors, primarily associated with observed climate warming. As reported by Marosz, Miętus and Biernacik (2023), air temperatures across Poland increased 0.28°C per decade between 1951 and 2021, with the most rapid change recorded in the winter period. This temperature rise has led to a decline in the snow cover across Poland's lowland areas (Somorowska, 2024), while also accelerating terrestrial evaporation, particularly in summer months (Somorowska, 2022). This results in significant changes in water availability and decreases water infiltration and recharge of groundwater (Krogulec *et al.*, 2022). Another reasons for such a tendency are more frequent intensive rainfall events, which result in more surface runoff, combined with a decline in groundwater replenishment (Ferencz, Dawidek and Bronowicka-Mielniczuk, 2022). Moreover, these adverse climatic changes may be further amplified in Warsaw due to the presence of an urban heat island (Kuchcik *et al.*, 2014). Apart from climatic factors, direct anthropogenic activities, such as increased degree of imperviousness due to urbanisation, construction drainages, and groundwater intakes (Krogulec *et al.*, 2022) also lead to the decrease in the water table level in the shallowest groundwater aquifer across Warsaw (Krogulec *et al.*, 2020). In consequence, this reduction in groundwater levels has led to a noticeable decrease spring discharge. Urban sprawl, which increases artificial heat sources (Hajnrych, Blachowski and Worsa-Kozak, 2023), as well as rising air temperature and decline of snow cover additionally contribute to changes in spring water temperature. The mean and maximum annual value of temperature increased by as much as 2.0°C for the UKSW spring and 4.6°C for the UW N spring, respectively. Increase of the spring water temperature related with climate warming and urban sprawl was also documented in other geographic regions (Matsuyama, 2014).

Changes in spring water chemistry confirm the negative impact of human activities on groundwater across Warsaw. All springs have represented different hydrochemical water types in the past 60 years, which indicates changes in the city pressure over time. Currently, the UKSW spring is characterised by two-ionic water type, dominated by HCO_3^- and Ca^{2+}, with its hydrochemical composition having become simplified since the 1960s. This transformation could be primarily attributed to the presence of the Las Bielański Nature Reserve, which protects the infiltration area on the upper plain and mitigates the negative impact of surrounding urbanised areas. A similar buffering effect was also documented by Jekaterynczuk-Rudczyk *et al.* (2022) for springs in the Knyszyn Forest. The UW N and Piaseczyńska springs exhibited a different pattern, continuing to reflect changes in the concentrations of key contaminants (Cl^-, SO_4^{2-}). Earlier conclusions related to varying urbanisation impacts can be further supported by a comparison of dry residual values and *TDS,* as reported by Pich and Płochniewski (1968) and Cygański and Woźniak (1997a; 1997b). For the UKSW spring, the mean dry residue increased from 473 mg·dm^{-3} in 1964–1966 to 726 mg·dm^{-3} in 1988–1990, which is consistent with the current measurements (709 mg·dm^{-3}). However, the nitrate contamination was stable during the past 60 years, with concentrations reaching 89 mg·dm^{-3} in March 1966, which is similar to present-day values. In contrast, the UW N spring showed nearly stable mean dry residue and *TDS* over the same period (1957 mg·dm^{-3} in 1964–1966 and 1954 mg·dm^{-3} in 1988–1990), indicating a negative but relatively stable anthropogenic impacts (spring recharge area almost remained unchanged in the last years). In contrast, the Piaseczyńska spring experienced a significant increase of *TDS,* from 858 mg·dm^{-3} through 1180 mg·dm^{-3} in 1988–1990 to 1295 mg·dm^{-3} in the present study. This mirrored the gradual urbanisation and increase of stressor impacts across the Mokotów district.

CONCLUSIONS

1. The scale and timing of anthropopressure on the springs recharge area are reflected in the spatial variability of their water physico-chemical properties. Increased total dissolved solids (*TDS*) and high proportion of Cl^-, SO_4^{2-}, K^+, and Na^+ ions in the chemical composition of spring waters indicate significant groundwater pollution in the city's most developed zones. This degradation is attributed to a combination of present and past stressors. In contrast, the forested recharge area of the UKSW spring mitigates the negative impact of the city on groundwater chemistry. However, this setting also contributed to increased NO_3^- concentrations. Recent anthropogenic pressure was also confirmed by seasonal changes in the chemical composition of spring waters, documented primarily for Cl^-, SO_4^{2-}, HCO_3^-, and NO_3^- ions.
2. The observed decline in spring discharge and the gradual increase of water temperature are the effect of global warming and its consequences, such as air temperature rise, acceleration of evapotranspiration, decrease of snow cover, increased imperviousness surfaces, and artificial heat sources. The substantial transformation in spring water chemistry confirms the presence of numerous stressors altering the groundwater system. These include elevated levels of atmospheric pollution, dissolution of underground remains from historical human activities, and the application of road maintenance substances.
3. The results suggest the need for further protection of groundwater in Warsaw, mainly by mitigating potential stressors that negatively affect both quality and quantity of groundwater. This can be achieved through simultaneous implementation of several technical, political, and educational measures. Recommended actions include expanding biologically active surfaces, adopting environmentally friendly road maintenance practices, such as sand spreading, modernising the sewage system, as well as limiting vehicular traffic in the city centre.

CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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