PAN
POLSKA AKADEMIA NAUK

JOURNAL OF WATER AND LAND DEVELOPMENT

e-ISSN 2083-4535

ITP-PIB

Polish Academy of Sciences (PAN) Institute of Technology and Life Sciences – National Research Institute (ITP – PIB)

JOURNAL OF WATER AND LAND DEVELOPMENT
DOI: 10.24425/jwld.2026.2309
2026, No. 70 (VII–IX): 71–80

Assessment of physicochemical parameters of groundwater of Oligocene aquifers in Warsaw, Poland as reserves in emergencies

Karolina Bralewska*, Joanna Rakowska

Fire University, Institute of Safety Engineering, Juliusza Słowackiego St, 52/54, 01-629 Warsaw, Poland

* Corresponding author

RECEIVED 27.11.2025 ACCEPTED 27.03.2026 AVAILABLE ONLINE 07.08.2026

Abstract: The waters found in the Oligocene formations are widely recognised as an excellent source of high-quality drinking water that does not require pretreatment or disinfection. This study aimed to evaluate the physicochemical properties of groundwater of Oligocene aquifers in Warsaw, Poland, which occur at a depth of 200–300 m, to compare them with drinking water standards, and to determine their suitability for consumption in crisis situations. Water samples were collected from ten randomly selected wells. The parameters assessed included pH, conductivity, temperature, turbidity, water hardness, and the concentrations of the following ions: antimony, arsenic, chromium, cadmium, copper, nickel, aluminium, mercury, lead, fluoride, chloride, ammonium, nitrate, sulphate, sodium, and iron. The average values of all analysed parameters were below the maximum limits established for drinking water. However, chloride ion and iron levels exceeded permissible limits at one and two sampling points, respectively. Nevertheless, analysis of the remaining parameters at these specific measurement points suggests that these elevated levels are not caused by anthropogenic sources. The mean values of most of the parameters (16/19) aligned with the first groundwater quality class, indicating excellent quality. The research conducted indicates that Oligocene water is suitable for human consumption in emergency situations. However, it should be noted that the assessment did not consider the presence of microorganisms. The obtained results emphasise the importance of maintaining and regularly monitoring the quality of existing public water sources. Such measures are essential to ensure that these sources remain a reliable emergency water supply.

Keywords: crisis situations, Oligocene water, water pollution, water quality, water supply

INTRODUCTION

Water is an indispensable raw material for life. Access to clean water is essential for maintaining optimal health and ensuring food security, thereby contributing to social stability. The profound interdependence of human functionality and the operations of numerous sectors on water highlights the critical importance of the water supply system, especially during crises when disruptions can significantly affect public health and daily life. The water supply system, as a fundamental public good, requires appropriate management and protection against excessive or inappropriate use, particularly in the face of potential emergencies. Preparation of water reserves and rapid distribution mechanisms is necessary to ensure continued access during crisis situations (Bendz and Boholm, 2020). A crisis situation is defined as a circumstance that adversely affects the safety of people, important property, or the environment, thus imposing significant constraints on the activities of relevant public administration units due to insufficient available forces and resources (Ostrowska and Mazur, 2015). In the context of water supply, a crisis situation is defined as any situation that significantly reduces the availability of water for the inhabitants of a given commune (NIK, 2024).

There is a long list of potential threats that could escalate into a crisis for the water supply system in Poland. The first and most likely threat is flooding. This is because floods often cause the inundation of water intakes and treatment plants, as well as the degradation of water supply infrastructure. Other consequences can include deteriorating water quality at surface water intake points and the emergence of waterborne infectious diseases (Hammond *et al.*, 2015; Arrighi *et al.*, 2017). The second threat to the water supply system is persistent hydrological and soil drought. This leads to reduced yields from surface sources and lower groundwater levels. This may result in water supply restrictions, such as lower pressure, and even supply interruptions. Water supply crises can also be caused by outdated infrastructure. This makes them susceptible to failures such as burst mains, broken house connections, and malfunctioning pumps and filters. Such failures can result in long-term interruptions to the water supply, as was seen in Otwock, Poland, in April 2025, when the water supply network failed. During maintenance and repair work, a significant amount of sediment was released from the interior walls of the nearly 50-year-old water main. Consequently, around 60,000 residents were left without access to drinking or sanitary water for several days (Powiat Otwocki, 2025). Power outages and increasingly common blackouts are another threat to the continuity of the water supply system, as they can disrupt the operation of pumps and water treatment plants. According to Keller and Wilson (1992), threats to water supplies also include industrial pollution, which can contaminate surface water intakes due to industrial accidents or improper waste disposal. Biological contamination, such as *Escherichia coli* bacteria, can also enter water supply systems through damaged pipes or floodwaters inundating infrastructure. Improper operation of the infrastructure can also be a factor. When identifying threats to the water supply system, it is important to recognise the significance of water infrastructure within the context of the country's critical infrastructure. This makes the water supply system vulnerable to potential acts of sabotage or terrorist attacks, such as the deliberate introduction of chemical, biological, and radioactive (CBR) substances. Furthermore, as many systems rely heavily on telecommunications networks, cyberattacks that disrupt IT systems used for process control and damage critical components of the water supply infrastructure can also endanger water supplies (Keller and Wilson, 1992; Grigg, 2003; Bendz and Boholm, 2020).

As the largest and most populous city in Poland, Warsaw is particularly vulnerable to threats to its water supply infrastructure. According to the Warsaw Crisis Management Plan, failures in the water and sewage networks constitute a major threat to the safety of residents and the functioning of the city (Stołeczne Centrum Bezpieczeństwa, 2021). Water main failures in 2011, 2015, 2020, and 2026, which left hundreds of thousands of residents without water for at least several hours, as well as numerous failures caused by the frost wave at the end of January and February 2026, demonstrate that key water infrastructure in Warsaw is susceptible to disruption, both as a result of physical factors (e.g. pipeline damage) and environmental conditions (e.g. weather and flooding) (MPWiK, no date).

The internal rescue plans of water supply companies and the crisis management plans prepared at various levels of public administration consider various crisis scenarios for water utilities and methods of distributing drinking water in such situations (Szpak and Szczepanek, 2023). Where the treated water reservoir is not contaminated, the use of water reserves stored in reservoirs managed by water utilities is envisaged. Furthermore, if the quality requirements for drinking water are met, water resources from potential reserve sources, such as deep wells, can be used for distribution during emergencies. Bottled or bagged water is the most common form of water distribution in crisis situations, particularly during the initial stages. This is supplemented by various means of transport and distribution outside the water supply network, including water tankers, containers, and transport vehicles (Kramarczyk-Rosiak and Urban, 2024). In light of recent experience, the water distribution methods previously employed in Poland may be inadequate. One of the most significant challenges is ensuring the availability of tankers and water tankers, as well as adhering to hygiene and sanitary requirements for their proper use. This assertion is corroborated by the Report of the Supreme Audit Office (Pol.: Najwyższa Izba Kontroli – NIK) in Poland. The report, in conjunction with existing literature, highlights the importance of identifying alternative sources of drinking water in crisis situations (Boryczko and Rak, 2017; Szpak and Szczepanek, 2023; Kramarczyk-Rosiak and Urban, 2024; NIK, 2024).

Given the abundance of groundwater in Poland (Fig. 1), a potential source could be public deep wells, which are common in many Polish cities. A particular type of groundwater found in central Poland is water that occurs in Oligocene formations and is known as Oligocene water (Karwowska *et al.*, 2023). This unique type of water also occurs in other parts of the world where the appropriate geological conditions have developed, including in Mississippi in the United States, Tunisia, Egypt and the Rusko-Polański district in Russia (Gandl, 1979; Houatmia *et al.*, 2016; Kondratyeva *et al.*, 2023; Asmoay *et al.*, 2025). The depth of the aquifer and the stratigraphy of the overlaying rock formations cause the groundwater to undergo filtration. This process has the potential to purify water of microbiological and chemical contamination, thus eliminating the necessity for pretreatment and disinfection (John and Rose, 2005; Karwowska *et al.*, 2023). Moreover, Oligocene waters have high pressure and are almost completely natural. The Oligocene aquifer is associated with fine- and medium-grained Lower Oligocene glauconitic sands, and occurs at a depth of 200–300 m. In Poland, this aquifer covers the Warsaw Basin, which has an area of 14,928 km^2 and available resources of approximately 372,146 $m^3 \cdot day^{-1}$. The sediment thickness is 60–80 m, 75% of which comprises the aforementioned aquifers (Bażyński, 1996). Paleohydrogeological studies have shown that Oligocene formations in the Warsaw area are between 2,000 and 70,000 years old (Karwowska *et al.*, 2023). Currently, there are approximately 70 active Oligocene wells in Warsaw, located in various city districts and on both sides of the Vistula River (Urząd Miasta Stołecznego Warszawy, no date). The typical depth of Oligocene wells is 220–270 m, and their capacity is 30–50 $m^3 \cdot h^{-1}$ (Bażyński, 1996). The maximum possible intake of Oligocene water from wells in Warsaw is estimated at 20,000 $m^3 \cdot day^{-1}$ (Karwowska *et al.*, 2023). While this does not constitute a significant contribution to the city’s overall water supply quantitatively, this type of water can be treated as a valuable strategic reserve in crisis situations.

Despite the widespread use of Oligocene water in Poland, to the authors’ knowledge, no scientific publications have analysed its physicochemical safety and suitability as an emergency water source. The only existing studies in this area have assessed the sodium content of Oligocene water in the daily diet and the

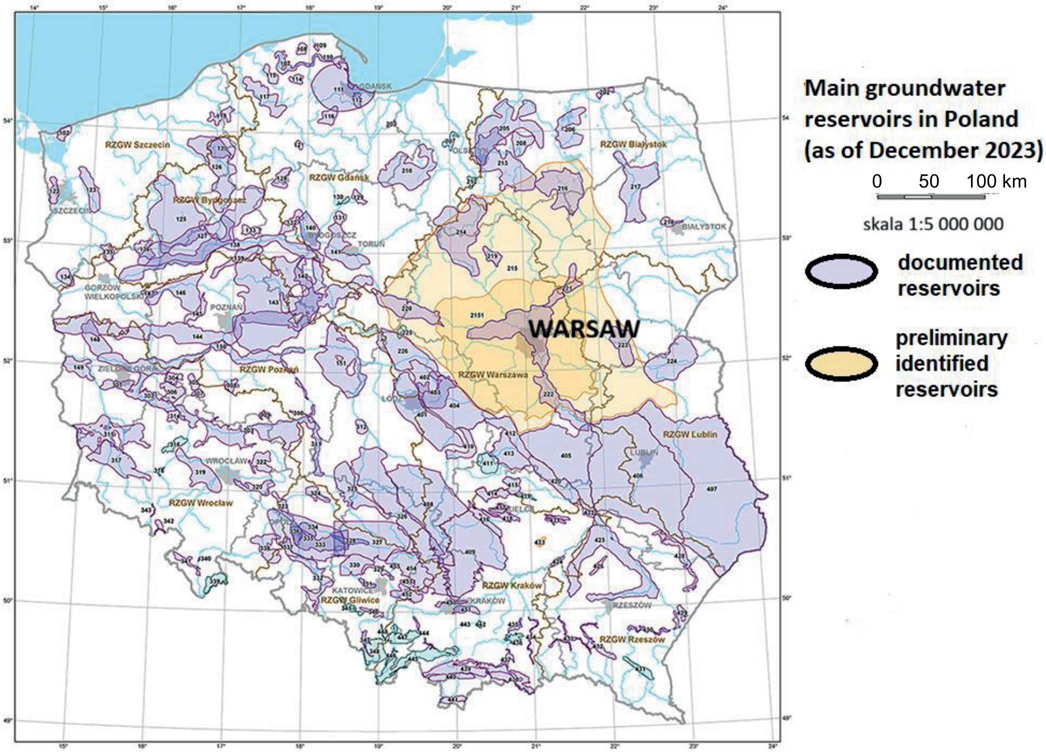

Fig. 1. Main groundwater reservoirs in Poland (as of December 2023); source: PIG-PIB (no date)

presence of potential microbiological contamination in randomly selected wells in Warsaw (Pietruszka and Kołłajtis-Dołowy, 2007; Karwowska *et al.*, 2023). The situation is slightly different in internationally, where there are many studies available on the physicochemical properties of underground waters, including those found in the Oligocene formations (Houatmia *et al.*, 2016; Kondratyeva *et al.*, 2023; Zhu *et al.*, 2024; Asmoay *et al.*, 2025). Given the popularity of Oligocene waters in Warsaw and the vulnerability of the city's infrastructure, particularly in the light of the climate crisis and the increasing number of armed conflicts in recent years, this study aims to analyse the basic physicochemical parameters of water collected from ten randomly selected Oligocene wells in Warsaw. The results will be compared with established standards for water intended for human consumption and the potential of Oligocene waters as an alternative source of drinking water in emergency situations will be evaluated (Directive, 2020).

MATERIALS AND METHODS

SAMPLING METHOD

Water samples were collected from ten randomly selected underground water wells located in different districts of Warsaw (both central and outlying) to get data representative for all the major districts of Warsaw. The wells under study were situated on the following streets: Ciszewskiego (P1), Dzierżoniowska (P2), Hozjusza (P3), Suwalska (P4), Maślaków (P5), Poborzańska (P6), Gąbińska (P7), Rozłogi (P8), Barska (P9), and Lizbońska (P10) (Fig. 2). The wells under study range in depth from 210 to 262 m. Water samples were collected between 08:00 and 11:00 a.m. in the period July 2024–April 2025. A total of six water samples were collected at each measurement point: two in spring (April), two in summer (July), and two in autumn (October). Each sample was collected separately. Regardless of the season, the temperature of the water samples was similar and ranged from 12.2 to 14.7°C. As the wells are used by residents, the tap was opened for 5–10 s to allow for maximum flow. The flow was then reduced, and the water was drained from the system until a constant temperature was achieved. Clean, dry glass bottles with a volume of 500 cm^3 were used for sampling. The samples were transported to the laboratory within two hours in refrigerators maintained at 8°C. After delivery to the laboratory, testing of the samples' physicochemical parameters was carried out the same day over the next few hours.

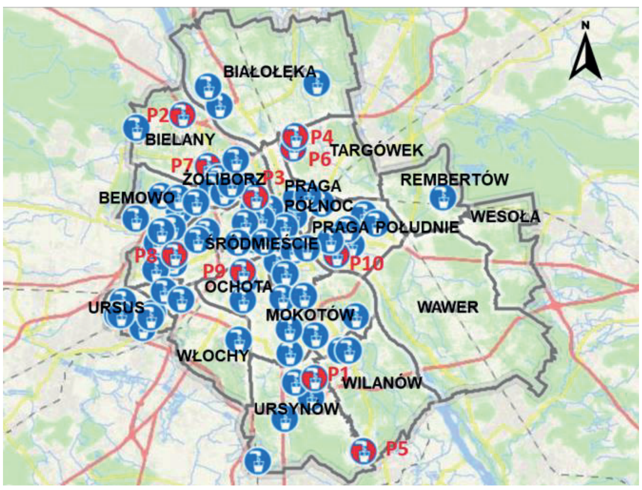

Fig. 2. Location of public Oligocene water wells in Warsaw with marked sampling points (red dots); P1–P10 = underground water wells; source: own elaboration based on the map of the City Hall of Warszaw (Urząd Miasta Stołecznego Warszawy, no date)

LABORATORY ANALYSES OF WATER

All analyses were carried out in accordance with the guidelines set out in Directive (2020) on the quality of water intended for human consumption. Physicochemical analyses of water included determining the following: water temperature (T), turbidity, pH, conductivity (EC), total hardness ($CaCO_3$), nitrate content (NO_3^-), ammonium ion content (NH_4^+), sulphate content (SO_4^{2-}), chloride ion content (Cl^-), fluoride ion content (F^-), and metal content, including antimony (Sb), arsenic (As), chromium (Cr), cadmium (Cd), copper (Cu), nickel (Ni), lead (Pb), mercury (Hg), aluminium (Al), and iron (Fe). Temperature, pH, and EC were measured in situ using a portable multimeter (CPC-411, Elmetron). Value pH was measured using a potentiometric method – ISO 10532:2020 (International Organization for Standardization, 2020) with a combined electrode (EPS-1) and an ECF-1 conductivity electrode. The pH electrode was calibrated using 6.00, 7.00, and 9.00 standards from AppliChem. The multimeter was also equipped with a CT2S-121 temperature sensor with a Pt-1000S resistor. Water turbidity was determined using the nephelometric method and an AL250T-IR turbidimeter – ISO 7027-1:2016 (International Organization for Standardization, 2016). Water hardness was determined by titration using the EDTA method with murexide as the indicator. Chloride ions in groundwater were determined by titration with silver nitrate ($AgNO_3$) in the presence of potassium chromate (K_2CrO_4) as an indicator (Mohr's method) – ISO 9297:1996 (International Organization for Standardization, 1996). The concentration of water-soluble inorganic cations and anions (NO_3^- SO_4^{2-}, NH_4^+, F^- and Na^+) was determined by ion chromatography (Dionex IC-90, Thermo Scientific) using a 250 mm × 4 mm AS22 column and a Dionex equivalent of the combined seven anion standard I for calibration. The content of selected metals was analysed using atomic emission spectroscopy with an induction-coupled (ICP-OES) plasma analyser (Thermo Scientific ICP-OES iCAP 7000) – ISO 11885:2009 (International Organization for Standardization, 2009). A multi-element ICP standard solution containing 1000 $mg \cdot dm^{-3}$ of the heavy metals, diluted in nitric acid (Merck, Germany), was used to prepare calibration curves (100, 200, 300, and 500 $mg \cdot dm^{-3}$). Deionised water with a conductivity of 6 $\mu S \cdot cm^{-1}$ was used for all auxiliary laboratory activities. To ensure accuracy and reliability, all measurement devices were calibrated according to the manufacturer's instructions. In addition to the samples, blanks and standard solutions were analysed for quality assurance and control purposes. Similarly, replicates were performed for some anomalous data to verify and confirm its consistency.

STATYSTICAL ANALYSIS

The data were analysed using Microsoft Excel (v. 2024, Microsoft Corporation, USA), and the statistical tests were performed using Jamovi (v.2.5, 2024). Statistical analyses were conducted to identify the dominant processes controlling the chemistry of the groundwater under study. Bartlett's sphericity test was performed with the mean values of the analysed physiochemical parameters for each Oligocene well as the dependent variable. The study aimed to ascertain whether there were any substantial correlations between specific parameters. Following the rejection of the hypothesis that there are no significant correlations between the variables, factor analysis and dimensionality reduction were conducted. The strategy employed in this study was principal component analysis (PCA) (Husson, Le and Pagès, 2017). Components were selected based on their respective eigenvalues. Following a thorough examination, components exhibiting eigenvalues greater than one were deemed worthy of further consideration (according to the Kaiser criterion). Loadings with absolute values ≥0.5 were considered significant. A Varimax rotation was employed in the analysis to maximise the explanatory power of a limited number of variables, thereby elucidating a multitude of factors. During the analysis, variables with zero variance across all samples were excluded.

WATER QUALITY ASSESSMENT METHODOLOGY

The quality of the water sampled from the Oligocene wells was assessed using two methods. First, the values of the parameters tested at the measurement points under study were compared with the limit values for specific groundwater quality classes, as specified in the Rozporządzenie (2019). The appropriate water quality class was then assigned to each sample. Additionally, the water quality index (WQI) was calculated. For groundwater, the contamination index (C_d), which was developed in accordance with the European Environment Agency's guidelines for groundwater quality, was used (Backman *et al.*, 1998; Anastasopoulos and Akratos, 2025). Contamination index evaluates groundwater contamination by examining ion concentrations and chemical species that exceed the maximum levels established for water quality suitable for human consumption. It is calculated as the sum of individual components that exceed the values set out in the relevant standard – in this case, the Directive (2020). C_d encompasses a larger number of parameters, including trace metals, due to their importance for groundwater quality and contamination. The C_d calculation was performed separately for each well. The contamination index summarises the combined effects of several quality parameters that are considered harmful to drinking water. Contamination index (C_d) is calculated according to Equation (1):

$$C_d = \sum_{i=1}^{n} C_{fi} \tag{1}$$

Contamination factor (C_{fi}) is calculated according to Equation (2):

$$C_{fi} = \frac{C_{Ai}}{C_{Ni}} - 1 \tag{2}$$

where: C_{fi} = contamination factor for the i-th component, C_{Ai} = analytical value of the i-th component, C_{Ni} = upper permissible concentration of the i-th component.

The elements and ionic species with analytical values below the upper permissible concentration values were not taken into consideration.

RESULTS AND DISCUSSION

As shown in Table 1, the values of the tested physical and chemical water parameters were averaged across all ten measurement points. The table also presents the values that water

Table 1. Statistical analysis of physicochemical variables of groundwater collected from 10 randomly selected water wells located in Warsaw, together with maximum values for drinking water

Variable	Unit	Min.	Max.	Mean	*SD*	MU	Standard
Turbidity	NTU	0.1	**1.2**	0.5	0.31	±0.2	1.0
T	°C	12.2	14.7	13.4	0.79	±1.0	–
pH	–	7.1	8.0	7.6	0.28	±0.2	6.5–9.5
EC	$\mu S \cdot cm^{-1}$	408.0	912.0	594.7	168.22	±91.0	2500.0
Sb	$\mu g \cdot dm^{-3}$	0.0	0.0	0.0	0.00	±0.2	10.0
As	$\mu g \cdot dm^{-3}$	0.0	0.0	0.0	0.00	±0.2	10.0
Cr	$\mu g \cdot dm^{-3}$	0.5	2.1	1.2	0.58	±0.2	25.0
F^-	$mg \cdot dm^{-3}$	0.1	0.8	0.5	0.23	±0.10	1.5
Cd	$\mu g \cdot dm^{-3}$	0.0	0.0	0.0	0.00	±0.010	5.0
Cu	$mg \cdot dm^{-3}$	0.0	0.7	0.3	0.20	±0.0015	2.0
Ni	$\mu g \cdot dm^{-3}$	4.0	9.0	6.2	2.17	±0.2	20.0
Pb	$\mu g \cdot dm^{-3}$	0.0	0.0	0.0	0.00	±0.2	5.0
Hg	$\mu g \cdot dm^{-3}$	0.0	0.0	0.0	0.00	±0.03	1.0
Al	$\mu g \cdot dm^{-3}$	1.4	20.0	12.3	7.87	±2.0	200.0
NO_3^-	$mg \cdot dm^{-3}$	0.3	4.1	2.5	1.49	±0.9	50.0
NH_4^+	$mg \cdot dm^{-3}$	0.1	0.4	0.2	0.12	±0.07	0.5
Cl^-	$mg \cdot dm^{-3}$	100.0	**350.0**	164.1	74.10	±13.0	250.0
$CaCO_3$	$mg \cdot dm^{-3}$	90.0	300.0	147.2	66.21	±22.0	60–500
Na^+	$mg \cdot dm^{-3}$	4.5	138.0	51.2	75.27	±21.0	200.0
SO_4^{2-}	$mg \cdot dm^{-3}$	15.0	70.0	40.3	27.75	±2.0	250.0
Fe	$\mu g \cdot dm^{-3}$	34.0	**340.0**	132.9	104.75	±20.0	200.0

Explanations: *T* = temperature; *EC* = conductivity, $CaCO_3$ = total water hardness, *SD* = standard deviation, MU = measurement uncertainty; values exceeding permissible concentrations are bolded.
Source: own study and Directive (2020).

intended for human consumption should meet, as specified in European legislation. These values are derived from the Directive (2020).

The first parameter analysed was turbidity. The turbidity levels of the collected samples ranged from 0.1 to 1.2 nephelometric turbidity units (NTU). The highest turbidity level, which exceeded the level of 1 NTU, was recorded at point P6 (Fig. 3). As turbidity at the other sampling points was approximately twice as low, the high value at point P6 may be due to technological defects in the borehole or the age of the pipeline. The increased turbidity could also be caused by geogenic contamination resulting from water infiltration from the Miocene level (Karwowska *et al.*, 2023). The temperature of the collected Oligocene water, measured immediately after sampling, ranged from 12.2 to 14.7°C. The temperature of the water samples was similar regardless of the season. This is because, at a depth of over 200 m, there is a zone of constant temperature and the influence of the atmosphere disappears. Consequently, the authors disregarded the influence of seasonality and related temperature variability in their study. The results of the conducted tests indicated minor fluctuations in the pH level, which ranged from 7.1 to 8.0, with an average of 7.6. The pH values at each measurement point were found to be within the range suitable for drinking water. Additionally, the majority of measurement points exhibited a slightly alkaline reaction, widely regarded as beneficial for human consumption as it helps maintain optimal acid-base balance in the body (Khanoranga and Khalid, 2019; Boukich *et al.*, 2025). In the case of electrolytic conductivity (*EC*), the recorded values show greater variation. The minimum conductivity recorded was 408 $\mu S \cdot cm^{-1}$, while the maximum was 912 $\mu S \cdot cm^{-1}$. Similar to the pH, the average conductivity of Oligocene water and the conductivity values at specific measurement points both remain below the upper limit set out in the regulatory framework for water intended for human consumption. Discrepancies in conductivity values at different measurement points may indicate variations in the concentration of dissolved substances in deep wells. These variations may be linked to the different chemical composition of the soil at the measurement location. The chemical composition of soil depends on the type of underlying rock and humus content, as well as the type of human activity (Zhu *et al.*, 2024; Boukich *et al.*, 2025). The primary human-related factors that may affect the quality of groundwater at the measurement points under study include earthworks related to the construction of the metro, tram routes, and ring roads; as well as the associated groundwater pumping and land drainage. Other factors include agricultural and horticultural activities carried out on an industrial scale on the outskirts of the city, and the associated irrigation that causes the leaching of salts

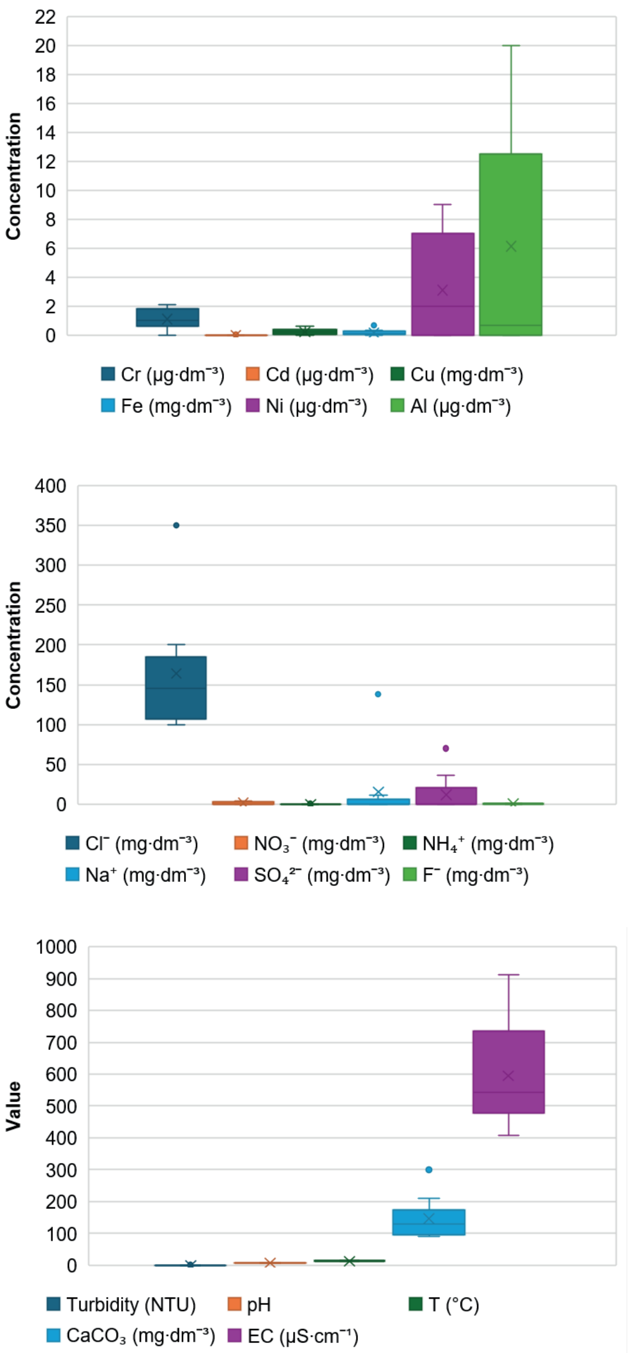

Fig. 3. Ranges of mean (from three samplings) values of physicochemical parameters of groundwater collected from 10 randomly selected water wells located in Warsaw; boxes show ranges between the 25th and 75th percentiles, whiskers extend from the box edges to the 5th and 95th percentiles of the data, dots indicate outliers, the horizontal line inside indicates the median value, and the cross indicates the mean; source: own study

from the soil (Zhu *et al.*, 2024; Boukich *et al.*, 2025). The empirical findings corroborate this phenomenon, as the highest conductivity values were recorded in areas with minimal industrialisation and no ongoing earthworks at the time of measurement: Żoliborz (P3) and Bielany (P7). The lowest conductivity values were recorded at measurement points in the Targówek (P4) and Bemowo (P8) districts, where metro construction was completed two years before the measurements. These areas also have a long history of agriculture.

As shown in Table 1, the concentrations of toxic ions and metals, such as F^-, Sb, As, Cr, Cu, Cd, Pb, Hg, Al, and Ni, were all found to be below the permissible values set out in the Directive (2020). Notably, the concentrations of Sb, As, CN^-, Cd, Pb, and Hg were found to be below the detection limit. These results suggest that anthropogenic sources are not influencing the concentrations of the aforementioned heavy metals. Conversely, the concentrations of Ni, Al, and Cr were higher at measurement points located in the most remote and developing districts of the city (P6, P7, P8 and P9), where intense development and earthworks related to the construction of the metro, tram and roads construction have recently taken place, than in city centre districts (P1, P2 and P3) (Fig. 3). However, given that these works are conducted at a maximum depth of 30 m, it is questionable whether they have impacted the quality of Oligocene waters, as these investments contaminate groundwater (subsurface). Another factor that could have influenced the differences in the concentrations of the analysed elements is the condition of the deep water intake installations, i.e. how frequently a given well is used. Observations conducted during the measurements indicate that Oligocene water is more popular in the city centre than in its outlying districts.

The mean concentrations of nitrate (NO_3^-) and ammonium (NH_4^+) ions were also below the limit value specified in the Directive (2020) on the quality of water intended for human consumption. NO_3^- concentrations ranged from 0.3 to 4.1 mg·dm^{-3} with an average of 2.5 mg·dm^{-3}, while NH_4^+ concentrations ranged from 0.06 to 0.44 mg·dm^{-3} with an average of 0.2 mg·dm^{-3}. NO_3^- concentrations are low because the underground waters, particularly those found in the Oligocene formations, are characterised by reducing (anaerobic) conditions, in which nitrates undergo denitrification, e.g. in ammonia. In exceptional circumstances, such as if Oligocene water becomes locally aerated due to operational errors, the natural ammonium nitrogen present in the water may oxidise to nitrates. This could explain the presence of these compounds in the tested samples (Calabrese, Campanale and Iurino, 2024). The ammonia found in the tested water samples may be the result of the decomposition of nitrates. This is because Oligocene formations (such as sands and mudstones) often contain clay minerals or organic residues, which are the original source of ammonium nitrogen (Mingram *et al.*, 2005; Calabrese, Campanale and Iurino, 2024).

The next parameter examined was chloride ions (Cl^-), which are an indicator of evaporite rocks dissolution, such as halite, but may also be a result of human activity (Rao *et al.*, 2024). The Cl^- concentration at the measurement points under study ranged from 100 to 350 mg·dm^{-3}, with an average of 164 mg·dm^{-3}. At one of the ten measurement points (designated point P6), the Cl^- concentration exceeded the permissible value of 250 mg·dm^{-3}. The turbidity level at this particular measurement point was also found to exceed the acceptable limit for drinking water. However, since the other parameters meet the drinking water requirements and were at relatively low levels, it can be concluded that the high chloride and turbidity concentrations at this measurement point were probably due to rock dissolution (Panno *et al.*, 2006). In the case of total water hardness, expressed as $CaCO_3$ concentration, the values of this parameter varied depending on the measurement point. The lowest concentration, indicating very soft water, was 90 mg·dm^{-3} at point P10. The highest concentration, indicating significantly hard water, was

300 mg·dm^{-3} at point P4. As the compounds that determine water hardness (i.e., calcium and magnesium) originate primarily from the dissolution of carbonates (calcite and dolomite), the variations in water hardness across different measurement points are likely to be related to the substrate's type and composition (Rao *et al.*, 2024; Boukich *et al.*, 2025; Hari *et al.*, 2025). The influence of the technological condition of the water intake installation cannot be ruled out, particularly given that the increase in hardness observed in the study was point-specific (Fig. 3). Other ions related to the substrate's type and composition include sodium (Na^+) and sulphates (SO_4^{2-}). Concentrations of Na^+ ranged from 4.5 to 138 mg·dm^{-3}, averaging 51.2 mg·dm^{-3}, while concentrations of SO_4^{2-} ranged from 15.0 to 70.0 mg·dm^{-3}, averaging 40.3 mg·dm^{-3}. Both Na^+ and SO_4^{2-} concentrations meet the requirements for drinking water.

The next parameter tested was iron (Fe). The concentration of this element varied depending on the measurement point. The lowest concentration (34 μg·dm^{-3}) was recorded at point P1, while the highest concentration (340 μg·dm^{-3}) was recorded at point P5. Two out of ten of the tested locations had Fe concentrations above 200 μg·dm^{-3} and therefore do not meet the requirements for water intended for human consumption. The presence of iron in groundwater is most often related to geogenic factors, i.e., factors related to the characteristics of the substrate. However, anthropogenic factors can also influence the concentrations of this element. In the case of Warsaw, these factors may be transportation or ironworks; however, confirmation of this hypothesis requires additional research.

As shown in Table 1, the average values for each analysed parameter, averaged across all ten measurement points under study, were lower than the limit values specified in the Directive (2020) on the quality of water intended for human consumption. Furthermore, analysing the values of the parameters at individual measurement points makes it difficult to determine where the highest values of several parameters would be found. Based on this, one can exclude the strong impact of anthropogenic sources (e.g., industrial activity and traffic emissions) on the concentrations of these elements and, thus, on the quality of the analysed groundwater. The standard deviation results (0.00–168.22) reveal significant dispersion of the studied parameters, reflecting the influence of various hydrogeochemical processes. The greatest variability was seen in compounds related to substrate characteristics, such as *EC*, Fe, Cl^-, $CaCO_3$, and Na^+. These differences reflect the variety of mechanisms controlling the chemical composition and spatial variability of groundwater (Rao *et al.*, 2024).

To verify the processes identified as controlling the chemistry of Oligocene waters in Warsaw, a principal component analysis (PCA) was performed. The data were examined using Bartlett's test, which yielded $p < 0.001$ for the null hypothesis. These results confirm that employing PCA in the analysis of results is statistically justified. This analysis included thirteen variables: (NO_3^-, NH_4^+, Cl^-, SO_4^{2-}, Na^+, Ca^{2+}, HCO_3^-, Fe, Al, Cr, Ni, Cu, and F^-). As a result of the PCA, three principal components (PC1–PC3) with eigenvalues greater than 1.0 were identified, explaining 74.6% of the variability of the studied parameters (Tab. 2). PC1 explains 41.31% of the total variance, PC2 explains 20.66%, and PC3 explains 12.63%.

PC1 differentiates between waters in terms of their trace metal content (positive loadings from Ni, Cr, F^- and Al) and

Table 2. The principal component analysis (PCA) components with eigenvalue higher than 1 identified for all ten Oligocene wells

Parameter	PC1	PC2	PC3	Uniqueness
NO_3^-	−0.361	0.213	−0.205	0.098
Cr	0.334	−0.277	0.014	0.531
F^-	0.355	0.184	0.057	0.153
Cu	0.037	−0.545	0.275	0.44
Ni	0.384	−0.161	−0.174	0.334
Al	0.281	0.254	−0.196	0.096
NH_4^+	−0.091	0.12	**0.696**	0.048
Cl^-	0.239	−0.019	−0.307	0.016
SO_4^{2-}	−0.212	0.278	−0.111	0.082
Na^+	−0.113	0.401	0.156	0.016
Fe	−0.267	−0.301	0.164	0.154
Ca^+	−0.324	−0.238	−0.289	0.508
HCO_3^-	−0.324	−0.238	−0.289	0.525

Explanations: PC1, PC2, PC3 = principal components; values exceeding permissible concentrations are bolded.
Source: own study.

parameters related to carbonate mineralisation (negative loadings from Ca^{2+} and HCO_3^-; for the PCA analysis, Ca^{2+} and HCO_3^- concentrations were estimated based on the total hardness). This pattern indicates two dominant processes: the interaction of lithology and the mobilisation of trace elements in the sedimentary environment, and the dissolution of carbonate minerals, which are responsible for water hardness and alkalinity. PC1 probably reflects the overall mineralisation processes associated with prolonged water–rock interaction within the confined aquifer system (Voutsis *et al.*, 2015; Otmani *et al.*, 2023).

PC2 exhibits the highest positive loadings for Na^+ and SO_4^{2-}, and the highest negative loadings for Cu and Fe. This structure may indicate ion exchange processes and variability in redox conditions, both of which influence the mobility of iron and transition metals. Conversely, the presence of sodium and sulphates may suggest local variations in mineralisation levels or secondary chemical transformations within the aquifer. Therefore, PC2 represents a hydrogeochemical factor associated with ionic transformations and variability in redox conditions (Jiang *et al.*, 2015; Voutsis *et al.*, 2015; Li *et al.*, 2025).

PC3 is clearly dominated by high positive NH_4^+ loadings. This suggests that variations in ammonium concentrations are a relatively independent factor in shaping the chemical composition of the studied waters. Under the hydrogeological conditions of the Oligocene formation, this may indicate the presence of local reducing environments that favour the ammonification or nitrification of organic matter (Jiang *et al.*, 2015).

The absence of a distinct anthropogenic component (e.g. NO_3^-, SO_4^{2-}, Cl^-) indicates limited human impact on the analysed groundwater system. These findings confirm the hydrochemical stability and homogeneity of the Oligocene aquifer in Warsaw (Li *et al.*, 2025).

Analysis of uniqueness values indicates that the variability of parameters such as Cl^-, Na^+ and NH_4^+ is largely explained by the isolated components, suggesting a strong connection with the main hydrogeochemical processes. However, the higher uniqueness values for Ca^{2+} and CO_3^- suggest that the processes controlling carbonate mineralisation may be more complex, and hat these processes are not fully captured by the first three components.

Table 3 shows the groundwater quality classes, which are based on the limit values specified in the Rozporządzenie (2019).

According to the literature, the degree of groundwater contamination is depicted using a three-grade scale as follows: low – C_d < 1, medium – C_d 1–3 and high – C_d > 3 (Backman *et al.*, 1998; Anastasopoulos and Akratos, 2025). Therefore, it can be concluded from the calculations performed on the basis of the values of individual tested parameters and permissible values that the contamination of water from each of the ten Oligocene wells under study is low.

Table 3. Water quality classes to which the measured values of individual parameters correspond and values of contamination index (C_d), depending on the location

Parameter	Class I	Class II	Class III	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
T (°C)	<10	12	16	III	II	III	III	III	III	III	III	III	III
pH	6.5–9.5			I	I	I	I	I	I	I	I	I	I
EC (μS·cm^{-1})	700	2500	2500	I	I	II	I	I	II	II	I	I	I
Sb (μg·dm^{-3})	5	5	5	I	I	I	I	I	I	I	I	I	I
As (μg·dm^{-3})	10	10	20	I	I	I	I	I	I	I	I	I	I
Cr (μg·dm^{-3})	10	50	50	I	I	I	I	I	I	I	I	I	I
F (mg·dm^{-3})	0.5	1	1.5	I	I	II	I	I	II	II	I	II	III
Cd (μg·dm^{-3})	1	3	5	I	I	I	I	I	I	I	I	I	I
Cu (mg·dm^{-3})	10	50	200	I	I	I	I	I	I	I	I	I	I
Ni (μg·dm^{-3})	5	10	20	I	I	I	I	I	II	I	II	II	I
Pb (μg·dm^{-3})	10	25	100	I	I	I	I	I	I	I	I	I	I
Hg (μg·dm^{-3})	1	1	1	I	I	I	I	I	I	I	I	I	I
Al (μg·dm^{-3})	100	200	200	I	I	I	I	I	I	I	I	I	I
NO_3^- (mg·dm^{-3})	10	25	50	III	I	I	I	I	I	I	I	I	I
NH_4^+ (mg·dm^{-3})	0.5	1	1.5	I	I	I	I	I	I	I	I	I	I
Cl^- (mg·dm^{-3})	60	150	250	II	III	II	II	III	IV	III	II	III	III
Na^+ (mg·dm^{-3})	60	200	200	I	I	I	I	I	I	I	I	I	I
SO_4^{2-} (mg·dm^{-3})	60	250	250	III	I	I	I	I	I	I	I	I	I
Fe (μg·dm^{-3})	200	1000	5000	I	I	I	II	II	I	I	I	I	I
C_d				0.0	0.0	0.0	0.2	0.7	0.6	0.0	0.0	0.0	0.0

Explanations: P1–P10 = underground water wells, location as in Fig. 2.
Source: own elaboration based on Rozporządzenie (2019).

It also shows the contamination index (C_d) values. Generally, most parameter values correspond to the first groundwater quality class, indicating the relatively good quality of the collected water. However, at each measurement point, the chloride ion concentrations and temperature exceed the limit value for class I, and at location P6, the Cl^- concentrations correspond to class IV. At half of the measurement points, the concentrations of F ions also exceed the permissible values for class I, while Ni concentrations at three-tenths of the measurement points correspond to class II. Furthermore, at the first measurement point, the NO_3^- and SO_4^{2-} concentrations indicate that the water is of class III quality. It should be noted that classifying a parameter as class III does not disqualify the water from being used as drinking water, as it still meets the standards specified in the relevant regulations (Directive, 2020).

CONCLUSIONS

Research into the concentrations and values of selected water parameters, collected from ten randomly selected wells in Warsaw, provides the following conclusions.

- The average values for pH, electrical conductivity, turbidity, and total hardness, as well as the concentrations of antimony, arsenic, chromium, fluoride, cadmium, copper, nickel, lead, mercury, aluminium, nitrates, ammonium, chlorides, sodium, sulphates, and iron, meet the specified drinking water standards. However, considering the results for individual measurement points reveals that the chloride ion concentration exceeds the maximum value for drinking water at one measurement point, and the iron concentration exceeds the specified parametric value at two measurement points.

- Initially, the research excludes an impact of anthropogenic sources on the quality of groundwater in Warsaw. This indicated that the natural hydrogeochemical processes are the determinant of water quality at the analysed measurement points.
- The preliminary assessment of the suitability of Oligocene water in Warsaw indicates that most wells could serve as alternative sources of drinking water in crisis situations (e.g. the detection of bacteria, the exceedance of selected physicochemical parameters in tap water, damage to water infrastructure facilities, CBRN (chemical, biological, radiological, nuclear) events, and contamination of water supply networks). Moreover, most of the tested parameters indicate the high quality of this type of water.
- In order to ensure the readiness of the Oligocene wells as an alternative source of drinking water in crisis situations, it is necessary to carry out an inventory of their technical condition and ensure they are maintained in proper technical and sanitary condition.
- This paper presents the results of preliminary studies which identified several limitations. The main restriction, particularly when comparing results across locations, is the relatively limited scope of the research. This covered only selected basic physicochemical parameters and a relatively small number of repetitions. The research conducted demonstrates the need for more extensive research encompassing a wider range of parameters (e.g. simultaneous physicochemical and microbiological parameters), lower detection limits, and a larger number of samples collected from each location. This would enable correlations to be analysed among the different water quality parameters across the study areas and the factors that determining the analysed parameters to be identified more precisely (e.g. in the form of a Piper chart or a more detailed principal component analysis (PCA) analysis for each measurement point).

FUNDING

The article was developed as part of research carried out in the project entitled "Comprehensive Hazard Identification, and Monitoring systEm for uRban Areas"-GA 101121342, acronym CHIMERA.

CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

REFERENCES

Anastasopoulos, P. and Akratos, Ch.S. (2025) "A review on water quality indices," *Hydroecology and Engineering*, 2, 10003. Available at: https://doi.org/10.70322/hee.2025.10003.

Arrighi, Ch. *et al.* (2017) "Flood impacts on a water distribution network," *Natural Hazards and Earth System Sciences*, 17(12), pp. 2109–2123. Available at: https://doi.org/10.5194/nhess-17-2109-2017.

Asmoay, A.A. *et al.* (2025) "Groundwater quality assessment and health risk analysis of Middle Eocene and Oligocene–Pleistocene aquifers in West Mallawi, Egypt," *Environmental Geochemistry and Health*, 47, 527. Available at: https://doi.org/10.1007/s10653-025-02799-w.

Backman, B. *et al.* (1998) "Application of a groundwater contamination index in Finland and Slovakia," *Environmental Geology*, 36, pp. 55–64. Available at: https://doi.org/10.1007/s002540050320.

Bażyński, J. (1996) "Woda poziomu oligoceńskiego na tle zaopatrzenia Warszawy w wodę do picia [Oligocene water level in the context of Warsaw's drinking water supply]," *Przegląd Geologiczny*, 44, pp. 391–393. Available at: https://geojournals.pgi.gov.pl/pg/article/view/17598/14203 (Accessed: June 13, 2025).

Bendz, A. and Boholm, A. (2020) "Indispensable, yet invisible: Drinking water management as a local political issue in Swedish municipalities," *Local Government Studies*, 46(5), pp. 800–819. Available at: https://doi.org/10.1080/03003930.2019.1682557.

Boryczko, K. and Rak, J. (2017) *Bezpieczeństwo systemów wodociągowych: Dywersyfikacja zasobów wody [Water supply system safety: diversifying water resources]*. Rzeszów, Poland: Oficyna Wydawnicza Politechniki Rzeszowskiej.

Boukich, O. *et al.* (2025) "Assessment of groundwater quality for irrigation using a new customized irrigation water quality index," *Journal of Hydrology: Regional Studies*, 59, 102346. Available at: https://doi.org/10.1016/j.ejrh.2025.102346.

Calabrese, A., Campanale, M. and Iurino, F. (2024) "Nitrate and ammonia contamination of groundwater and their effect on microbial community in Apulia Region," *Ecological Engineering & Environmental Technology*, 25(6), pp. 371–382. Available at: https://doi.org/10.12912/27197050/186493.

Directive (2020) "Directive (EU) 2020/2184 of the European Parliament and of the Council of 16 December 2020 on the Quality of Water Intended for Human Consumption," *Official Journal*, L 435/1. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32020L2184 (Accessed: June 15, 2025).

Gandl, L.A. (1979) *The Oligocene aquifer system in Mississippi. Water-Resources Investigations Report*, 79–28. U.S. Geological Survey. Available at: https://doi.org/10.3133/wri7928.

Grigg, N.S. (2003) "Water utility security: Multiple hazards and multiple barriers," *Journal of Infrastructure Systems*, 9(2), pp. 81–88. Available at: https://doi.org/10.1061/(ASCE)1076-0342(2003)9:2(81).

Hammond, M.J. *et al.* (2015) "Urban flood impact assessment: A state-of-the-art review," *Urban Water Journal*, 12(1), pp. 14–29. Available at: https://doi.org/10.1080/1573062X.2013.857421.

Hari, R. *et al.* (2025) "Machine learning and GIS based groundwater quality prediction for agricultural practices – A case study form Arjunanadi River basin of South India," *Computers and Electronics in Agriculture,* 229, 109932. Available at: https://doi.org/10.1016/j.compag.2025.109932.

Houatmia, F. *et al.* (2016) "Basin structure and water quality of the Oligocene aquifer in the Sebkhet El Behira basin (central Tunisia)," *Hydrological Sciences Journal*, 61(5), pp. 868–880. Available at: http://dx.doi.org/10.1080/02626667.2015.1008481.

Husson, F., Le, S. and Pagès, J. (2017) *Exploratory multivariate analysis by example using R.* New York: CRC. Available at: https://doi.org/10.1201/b21874.

ISO 7027-1:2016. *Water quality – Determination of turbidity*. International Organization for Standardization.

ISO 9297:1996. *Water quality – Determination of chloride – Silver nitrate titration with chromate indicator (Mohr's method)*. International Organization for Standardization.

ISO 10532:1995. *Earth-moving machinery – Machine-mounted retrieval device – Performance requirements*. International Organization for Standardization.

ISO 11885:2009. *Water quality – Determination of selected elements by inductively coupled plasma optical emission spectrometry (ICP-OES)*. International Organization for Standardization.

Jiang, Y. *et al.* (2015) "Principal component analysis and hierarchical cluster analyses of arsenic groundwater geochemistry in the Hetao basin, Inner Mongolia," *Geochemistry*, 75(2), pp. 197–205. Available at: https://doi.org/10.1016/j.chemer.2014.12.002.

John, D.E. and Rose, J.B. (2005) "Review of factors affecting microbial survival in groundwater," *Environmental Science & Technology,* 39(19), pp. 7345–7356. Available at: https://doi.org/10.1021/es047995w.

Karwowska, E. *et al.* (2023) "Microbiological hazards associated with the use of Oligocene waters: A study of water intakes in Warsaw, Poland," *Microorganisms,* 11(4), 826. Available at: https://doi.org/10.3390/microorganisms11040826.

Keller, A. and Wilson, H.C. (1992) *Hazards to drinking water supplies*. London: Springer. Available at: https://doi.org/10.1007/978-1-4471-3187-8.

Khanoranga and Khalid, S. (2019) "An assessment of groundwater quality for irrigation and drinking purposes around brick kilns in three districts of Balochistan Province, Pakistan, through water quality index and multivariate statistical approaches," *Journal of Geochemical Exploration*, 197, pp. 14–26. Available at: https://doi.org/10.1016/j.gexplo.2018.11.007.

Kondratyeva, T.L. *et al.* (2023) "State, problems and prospects of water supply for small settlements on the example of the Russko-Polyansky district of the Omsk region," *AIP Conference Proceedings*, 2812(1). Available at: https://doi.org/10.1063/5.0163594.

Kramarczyk-Rosiak, K. and Urban, A. (2024) "Zaopatrzenia w wodę w sytuacjach kryzysowych – zapewnienie mieszkańcom gmin bezpieczeństwa dostaw [Water supply in crisis situations – Ensuring the security of supply to residents of municipalities]," *Kontrola Państwowa*, 69(3), pp. 33–43. Available at: https://doi.org/10.53122/ISSN.0452-5027/2024.1.18.

Li, Ch. *et al.* (2025) "Differential evolution in hydrochemical characteristics amongst porous, fissured and karst aquifers in China," *Hydrology*, 12(7), 175. Available at: https://doi.org/10.3390/hydrology12070175.

Mingram, B. *et al.* (2005) "The significance of fixed ammonium in Palaeozoic sediments for the generation of nitrogen-rich natural gases in the North German Basin," *International Journal of Earth Science*, 94, pp. 1010–1022. Available at: https://doi.org/10.1007/s00531-005-0015-0.

MPWiK (no date) *Aktualności [News]*. Miejskie Przedsiębiorstwo Wodociągów i Kanalizacji w Warszawie. Available at: https://www.mpwik.com.pl/view/aktualnosci (Accessed: February 11, 2026).

NIK (2024) *Zapewnienie bezpieczeństwa zaopatrzenia w wodę wybranych jednostek samorządu terytorialnego na wypadek wystąpienia sytuacji kryzysowych [Ensuring the security of water supply to selected local government units in the event of crisis situations]*. Warszawa: Najwyższa Izba Kontroli. Available at: https://www.nik.gov.pl/kontrole/P/23/087/ (Accessed: June 10, 2025).

Ostrowska, M. and Mazur, S. (2015) "Risk in a crisis situation," *Procedia Economics and Finance*, 23, pp. 1054–1059. Available at: https://doi.org/10.1016/S2212-5671(15)00373-1.

Otmani, M. *et al.* (2023) "Trace metal elements in different categories of drinking water by exploratory analysis," *Applied Journal of Environmental Engineering Science*, 9(2), pp. 69–81. Available at: https://doi.org/10.48422/IMIST.PRSM/ajees-v9i2.38558.

Panno, S.V. *et al.* (2006) "Characterization and identification of Na-Cl sources in ground water," *Groundwater*, 44(2), pp. 176–187. Available at: https://doi.org/10.1111/j.1745-6584.2005.00127.x.

Pietruszka, B. and Kołłajtis-Dołowy, A. (2007) "Oligocene and bottled water as a source of sodium in everyday diet of adults," *Polish Journal of Food and Nutrition Sciences*, 57(2), pp. 247–252. Available at: https://journal.pan.olsztyn.pl/pdf-98059-30639?filename=30639.pdf (Accessed: June 13, 2025).

PIG-PIB (no date) *Baza danych o Głównych Zbiornikach Wód Podziemnych – GZWP [Database of Main Underground Water Reservoirs]*. Warszawa: Państwowy Instytut Geologiczny – Państwowy Instytut Badawczy. Available at: https://www.pgi.gov.pl/psh/dane-hydrogeologiczne-psh/947-bazy-danych-hydrogeologiczne/8890-gzwp.html (Accessed: June 13, 2025).

Powiat Otwocki (2025) *Informacje o awarii sieci wodociągowej w Otwocku [Information about the water supply network failure in Otwock]*. Available at: https://www.powiat-otwocki.pl/info/zawartosc/904/ (Accessed: June 13, 2025).

Rao, S. *et al.* (2024) "Hydrochemical characterization and water quality perspectives for groundwater management for urban development," *Groundwater for Sustainable Development*, 24, 101071. Available at: https://doi.org/10.1016/j.gsd.2023.101071.

Rozporządzenie (2019) "Rozporządzenie Ministra Gospodarki Morskiej i Żeglugi Śródlądowej z dnia 11 października 2019 r. w sprawie kryteriów i sposobu oceny stanu jednolitych części wód podziemnych [Regulation of the Minister of Maritime Economy and Inland Navigation of 11 October 2019 on the criteria and method of assessing the condition of groundwater bodies]," *Dz.U.* 2019 poz. 2148.

Stołeczne Centrum Bezpieczeństwa (2021) *Plan Zarządzania Kryzysowego m.st. Warszawy [Warsaw Crisis Management Plan]*. Warszawa: Urząd Miasta Stołecznego Warszawy.

Szpak, D. and Szczepanek, A. (2023) "A new method of water supply in crisis situation," *Water*, 15(17), 3160. Available at: https://doi.org/10.3390/w15173160.

Urząd Miasta Stołecznego Warszawy (no date) *Ujęcia wód podziemnych [Underground water intakes in Warsaw].* Available at: https://testmapa.um.warszawa.pl/mapa/2b202742-db53-4d95-a6ef-a2f03ff3650c (Accessed: June 13, 2025).

Voutsis, N. *et al.* (2015) "Assessing the hydrogeochemistry of groundwaters in ophiolite areas of Euboea Island, Greece, using multivariate statistical methods," *Journal of Geochemical Exploration*, 159, pp. 79–92. Available at: https://doi.org/10.1016/j.gexplo.2015.08.007.

Zhu, M. *et al.* (2024) "Assessment of groundwater quality of unconfined aquifers in an urbanized area using the water quality index method," *Environmental Science and Pollution Research,* 31 (56): 64870–83. Available at: https://doi.org/10.1007/s11356-024-35562-2.