

MULTI-INDICATOR ASSESSMENT OF GROUNDWATER FOR MUNICIPAL AND AGRICULTURAL PURPOSES IN SOUTH-WESTERN POLAND

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Abstract

The study focuses on a multi-indicator assessment of groundwater quality in south-western Poland with regard to its suitability for municipal and agricultural purposes. The Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI) was applied to evaluate water for drinking purposes, while Soluble Sodium Percentage (SSP), Sodium Adsorption Ratio (SAR), Kelley Ratio (KR), Magnesium Adsorption Ratio (MAR), and electrical conductivity (EC) indices were used to determine its quality for irrigation. The analysis covered data from 26 monitoring sites collected between 2005 and 2024, taking into account spatio-temporal variability as well as the influence of natural and anthropogenic factors. The results revealed considerable variability in water quality, with CCME WQI values in 2024 ranging from 49.62 to 100. The most significant negative impact on water quality was attributed to iron (Fe), manganese (Mn), and ammonium (NH₄⁺), showing strong negative correlations with the CCME WQI ($r = -0.898, -0.756, \text{ and } -0.575$, respectively). In some sites, exceedances of up to tenfold for Fe and fortyfold for Mn were recorded, which may pose risks to both human health and infrastructure. Irrigation suitability indices generally indicated good quality, although locally reduced suitability was observed, mainly related to elevated EC. The study demonstrates the necessity of a site-specific approach to managing groundwater quality, which takes into account local pollution sources and hydrogeological conditions. These findings could inform remedial actions, optimise water treatment and ensure the sustainable management of water resources in agriculture.

Keywords: groundwater, drinking water, irrigation, CCME WQI, salinity indicators

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1. INTRODUCTION

Access to safe drinking water and the sustainable management of water resources for irrigation represent key challenges in the modern world, particularly in regions with intensive agricultural and industrial activity. The assessment of groundwater quality is essential for protecting public health and the environment; however, due to the spatio-temporal variability of pollution sources, it remains a complex issue. The Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI) provides a comprehensive tool for evaluating the suitability of water for human consumption by aggregating numerous physicochemical parameters into a single value (Hurley et al. 2012). CCME WQI condenses many parameters into a single score and is flexible in parameter choice and standards, making it suitable where multiple natural and anthropogenic pressures act on groundwater (Ansari, et al. 2024, Alexakis, 2020, Alexakis, 2022, Haider et al. 2019). Meta-evaluation against EU Groundwater Directive classes showed CCME WQI gives relatively strict and realistic classifications for groundwater, closely matching regulatory thresholds. CCME-type indices were successfully applied to springs in southern Poland, classifying all sites as “Good” for drinking despite complex seasonal hydrochemistry (Eid et al. 2025). Similar applications in Hungary’s Great Plain and other European aquifers show CCME WQI can track improvement or deterioration of shallow groundwater in agricultural and rural settings (Alexakis, 2022, Calmuc et al. 2020, Mester et al. 2020). Nevertheless, its application in Central Europe, particularly in industrial, post-industrial and agricultural regions such as those found in south-western Poland, requires further investigation in view of local conditions, including anthropogenic pressures (e.g. mining, agriculture) and naturally elevated concentrations of elements such as iron and manganese. The rationale for undertaking this study arises from the lack of long-term, regionally focused analyses of groundwater quality in the Odra River basin, where both historical industrial activity and contemporary agricultural practices may negatively affect water resources. Although the CCME WQI has been widely applied in Canada and elsewhere (Bilgin, 2018), its suitability under Polish conditions has not been sufficiently examined. Similarly, indices used to assess irrigation suitability (e.g. SAR, SSP, KR) are well documented for arid regions (Subramanian and Baskar, 2022), yet their application in temperate climates, where the risk of salinisation is lower, warrants further study. This is particularly important as the migration of contaminants from agricultural fields and waste sites not only degrades irrigation water quality but also poses differentiated non-carcinogenic health risks to the local population (Paneerselvam et al. 2021, 2023b). In this context, EC classifies salinity hazard, critical for crop tolerance and soil structure; it is a primary screening tool in many irrigation studies from temperate and semi-arid regions (Uddin et al. 2023, Vranešević et al. 2024). SAR quantifies sodium relative to Ca and Mg, directly linked to soil dispersion and permeability loss (Uddin et al. 2023, Dhaoui et al. 2023). The presence of excess sodium and potassium in irrigation water adversely impacts soil structure, plant development, and the broader environment. Sodium ions promote soil compaction and reduce permeability, which is particularly detrimental for plants as it hampers the absorption of essential nutrients (Ayers and Westcot 1994; Małuszyńska and Małuszyński 2009). Furthermore, prolonged use of such water can lead to a significant loss of soil fertility and progressive groundwater salinisation (Kłosowska 2010). To address these risks, SSP and KR provide complementary sodium hazard views and are widely used together to classify water from excellent to unsuitable for irrigation. High MAR can damage soil structure and crop yield even when SAR is acceptable; MAR has been shown to sometimes classify waters as unsuitable where SAR alone suggests suitability, highlighting its added value. Additionally, indices such as MAR provide significant added value, as high magnesium concentrations can damage soil structure even when SAR levels appear acceptable (Vranešević et al. 2024, Awad et al. 2022, Papazotos et al. 2025). Excess magnesium weakens the bonds between soil particles, leading to the formation of compacted layers that limit air and water availability. Moreover, it competes with

calcium for cation exchange sites and interferes with potassium uptake, thereby inhibiting crop growth and reducing overall agricultural productivity (Lityński 1973). In recent years, concerns regarding groundwater degradation in Poland have intensified, linked to industrial emissions, agricultural nutrient runoff, and geological factors (Górski 2022; Kubicz et al. 2021). The discharge from households, septic tanks, and the intensive use of fertilizers are globally recognized as primary drivers of nitrate enrichment, necessitating spatial analysis to identify contamination hotspots (Panneerselvam et al. 2023a). Groundwater in south-western Poland is used for both drinking and irrigation, in a temperate climate with carbonate-rich and mixed-ion waters. Southern Poland springs and carbonate aquifers show Ca–Mg–HCO₃ and Ca–Mg–Cl/SO₄ facies with strong seasonal variation in Ca, Mg, Na, Cl and metals (5). Indices based on these major ions (EC, SAR, SSP, KR, MAR) directly reflect such facies and seasonal changes. Temperate climates with snowmelt and variable recharge produce time-dependent dilution and concentration. CCME-type WQI and EC/SAR-based irrigation indices have been effective in similarly temperate European and Mediterranean settings (Greece, Turkey, Hungary) (Arıman et al. 2024, Mester et al. 2020, Papazotos et al. 2025). However, comprehensive studies combining the evaluation of groundwater suitability for both drinking and irrigation remain scarce. Using CCME WQI for municipal suitability and EC, SAR, SSP, KR, MAR for irrigation is consistent with best practice. These indices are flexible, validated against EU standards, sensitive to both natural hydrochemistry and human impacts, and already successfully applied in Poland and comparable European regions. The chosen indicators (CCME WQI, SAR, SSP, KR, MAR, EC) jointly capture potability, salinity and sodicity risks, and are consistent with recent hydrochemical work in Poland.

The objectives of this study are therefore to:

1. Assess the variability of groundwater quality in south-western Poland using the CCME WQI, identifying key pollutants and their implications for human health and infrastructure.
2. Determine the suitability of groundwater for irrigation based on SSP, SAR, KR, MAR, and EC indices, with particular emphasis on soil degradation risks and plant toxicity.

The study is based on long-term data (2005–2024) from 26 monitoring sites, thereby addressing the knowledge gap regarding groundwater quality in this region. The findings provide a basis for implementing innovative measures in drinking water treatment and for optimising irrigation practices in agriculture.

2. METHODOLOGY

2.1. Characteristics of the CCME WQI for Assessing Drinking Water Suitability

The CCME WQI was introduced in Canada in 2001 for the assessment of surface waters (Lumbet al. 2006). It enables the evaluation of water suitability for drinking purposes by classifying the result into one of five categories, ranging from the highest to the lowest quality (Table 1).

Table 1. Classification of the CCME WQI (Khan et al. 2005)

No.	Rank	Value
1	Excellent	95 - 100
2	Good	80 - 94
3	Fair	65 - 79
4	Marginal	45 - 64
5	Poor	0 - 44

The overall CCME WQI score is derived from components referred to as F_1 , F_2 and F_3 :

F_1 (Scope) determines the percentage of indicators that do not meet the requirements in relation to water quality guidelines in the tested period:

$$F_1 = \left(\frac{\text{number of failed variables}}{\text{total number of variables}} \right) * 100 [\%] \quad (2.1.1)$$

where: number of failed variables - the number of variables that did not meet the water quality guidelines at least once during the assessment period; total number of variables - the total number of variables assessed.

F_2 (Frequency) determines the percentage of samples that do not meet the requirements:

$$F_2 = \left(\frac{\text{number of failed tests}}{\text{total number of tests}} \right) * 100 [\%] \quad (2.1.2)$$

F_3 (Amplitude) determines how much the measured values deviate from the permissible values:

$$F_3 = \left(\frac{\text{nse}}{0,01\text{nse}+0,01} \right) \quad (2.1.3)$$

If the sample value exceeds the specified limit, use the following formula:

$$\text{excursion} = \frac{\text{failed test value}}{\text{objective}} - 1 \quad (2.1.4)$$

If the sample value does not reach the required limit, use the following formula:

$$\text{excursion} = \frac{\text{objective}}{\text{failed test value}} - 1 \quad (2.1.5)$$

The counter shows the sum of all calculated 'excursion' cases.

$$\text{nse} = \frac{\sum_{i=1}^n \text{excursion } i}{\text{number of tests}} \quad (2.1.6)$$

where: nse (normalized sum of excursions) - the ratio of the sum of all excursion values to the total number of tests, excursion - the individual deviation of a test value from its guideline value.

The CCME WQI index is calculated using the following formula:

$$\text{CCME WQI} = 100 - \left(\frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1,732} \right) \quad (2.1.7)$$

Based on the result obtained, the tested area can be classified into one of the categories shown in Table 1.

The assessment used the limit values recommended in the Regulation of December 7, 2017, on the quality of water intended for human consumption (Dz. U. z 2017 r. poz. 2294). The limit values used in this study are presented in Table 2.

Table 2. Limit values for drinking water parameters

Sb	As	NO ₃ ⁻	B	Cr	CN ⁻	F	Cd	Cu	Ni	Pb	Hg
mg · dm ⁻³											
0.005	0.01	50	1.0	0.05	0.05	1.5	0.005	2.0	0.02	0.01	0.001
Al	NH ₄	Cl	SO ₄	Na	Fe	Mg	Ag	Se	Mn	PEW	pH
mg · dm ⁻³										μS · cm ⁻¹	(-)
0.2	0.5	250	250	200	0.2	7 - 125	0.001	0.01	0.05	2.50	6.5 - 9.5

2.2. Characteristics of indices for assessing irrigation water suitability

The SSP (Soluble Sodium Percentage) index defines the proportion of sodium and potassium relative to the total concentration of the major cations dissolved in water (Table 3) (Ukoha-Onuoha 2022).

$$SSP = \left(\frac{Na^{+} + K^{+}}{Ca^{2+} + Mg^{2+} + Na^{+} + K^{+}} \right) \cdot 100 (\%), \text{ where:} \quad (2.2.1)$$

Na⁺ - sodium ion concentration (mg · dm⁻³),

Ca²⁺ - calcium ion concentration (mg · dm⁻³),

Mg²⁺ - magnesium ion concentration (mg · dm⁻³),

K²⁺ - potassium ion concentration (mg · dm⁻³).

Table 3. Classification of water suitability – SSP index

SSP (%)	Rank
< 20	Excellent
20 - 40	Good
40 - 60	Acceptable
60 - 80	Questionable
> 80	Inappropriate

The SAR (Sodium Adsorption Ratio) index defines the proportion of sodium, expressed in ($\text{mg} \cdot \text{dm}^{-3}$), relative to the sum of calcium and magnesium. It enables the classification according to the potential impact of the water on soil structure degradation (Table 4) (Ukoha-Onuoha 2022).

$$\text{SAR} = \frac{\text{Na}^+}{\sqrt{\frac{\text{Ca}^{2+} + \text{Mg}^{2+}}{2}}} (\text{mg} \cdot \text{dm}^{-3}), \text{ where:} \quad (2.2.2)$$

Na^+ - sodium ion concentration ($\text{mg} \cdot \text{dm}^{-3}$),

Ca^{2+} - calcium ion concentration ($\text{mg} \cdot \text{dm}^{-3}$),

Mg^{2+} - magnesium ion concentration ($\text{mg} \cdot \text{dm}^{-3}$).

Table 4. Classification of water suitability – SAR index

SAR ($\text{mg} \cdot \text{dm}^{-3}$)	Rank
< 10	Excellent
10 - 18	Good
18 - 26	Satisfactory
> 26	Poor

The Kelley Ratio (KR) is a parameter used to assess irrigation water quality, indicating the impact of sodium ions on the soil's ability to maintain proper structure and permeability (Table 5) (Ukoha-Onuoha 2022).

$$\text{KR} = \frac{\text{Na}^+}{\text{Ca}^{2+} + \text{Mg}^{2+}} (\text{mg} \cdot \text{dm}^{-3}), \text{ where:} \quad (2.2.3)$$

Na^+ - sodium ion concentration ($\text{mg} \cdot \text{dm}^{-3}$),

Ca^{2+} - calcium ion concentration ($\text{mg} \cdot \text{dm}^{-3}$),

Mg^{2+} - magnesium ion concentration ($\text{mg} \cdot \text{dm}^{-3}$).

Table 5. Classification of water suitability – KR index

KR ($\text{mg} \cdot \text{dm}^{-3}$)	Rank
< 1	Safe
> 1	Unsafe

The Magnesium Adsorption Ratio (MAR) index defines the ratio of magnesium ions to the sum of calcium and magnesium ions. A high MAR value may indicate potential issues related to excessive magnesium in irrigation water, which can negatively affect soil properties and plant health (Table 6) (Acharya et al. 2018).

$$\text{MAR} = \frac{\text{Mg}^{2+}}{\text{Ca}^{2+} + \text{Mg}^{2+}} \cdot 100 (\%), \text{ where:} \quad (2.2.4)$$

Ca^{2+} - calcium ion concentration ($\text{mg} \cdot \text{dm}^{-3}$),

Mg^{2+} - magnesium ion concentration ($\text{mg} \cdot \text{dm}^{-3}$).

Table 6. Classification of water suitability – MAR index

MAR (%)	Rank
< 50	Appropriate
> 50	Inappropriate

High electrical conductivity (EC) indicates the degree of water salinity, affecting both soil and plants. It leads to the accumulation of salts in the soil, promoting salinisation, limiting plant growth, and hindering water uptake (Table 7). This results in increased soil compaction and reduced permeability, restricting oxygen and water availability to root systems. In the long term, excess salts can contribute to soil degradation, disrupting chemical balance and impairing the uptake of essential nutrients such as potassium and magnesium by plants (Widłak 2016).

Table 7. Classification of water suitability – EC

EC [$\mu\text{S} \cdot \text{cm}^{-1}$]	Impact on soil and plants
0 - 250	Low
251 - 750	Medium
751 - 2 250	High
2 251 - 6 000	Very high

2.3. Research material and area

The analyses were based on chemical analyses of groundwater belonging to the observational and research network of the Polish Geological Institute – National Research Institute (PIG – PIB). Groundwater samples were collected under the National Environmental Monitoring Programme in Poland between 2005 and 2024. The samples were part of diagnostic and operational groundwater monitoring programs coordinated by PIG-PIB and the Voivodeship Inspectorates for Environmental Protection (WIOŚ). The selection of monitoring points followed strict statutory criteria regarding location, the determination of an appropriate number of stations, and specific site conditions. This framework was designed to ensure a reliable assessment of groundwater quantity and available resources, while providing a holistic and consistent evaluation of chemical status. Such a network allows for the identification of significant and persistent upward trends in pollutant concentrations, effectively distinguishing them from natural variations with a high level of confidence and precision to allow for timely environmental protection measures. The sampling was strictly defined by the monitoring type: diagnostic monitoring was conducted between April and October, while operational monitoring was performed from March to June and from August to October. During fieldwork, key unstable parameters were measured directly at the site, including groundwater temperature, pH, electrical conductivity, and

dissolved oxygen. Field procedures followed the ISO 5667 series, specifically PN-EN ISO 5667-1 and PN-EN ISO 5667-11 (for groundwater collection). To ensure samples were representative of the formation water, wells were purged until field-measured parameters reached stability. Sample preparation and storage adhered to the PN-EN ISO 5667-3 standard. To ensure the reliability of the data, the sampling protocol included a rigorous quality control system. Sample sets delivered to the laboratory contained duplicate samples. Additionally, field-filtered blanks (for cations and anions) and transport blanks were utilized to monitor potential contamination during the sampling and transport process. All samples were stored in high-density polyethylene bottles, kept in cooling boxes at approximately 4°C, and transported to the laboratory within the required technical timeframe. Only results for which the analysis error did not exceed 10% were included in the study. Laboratory tests were carried out at the Chemical Laboratory (LCh) of the Polish Geological Institute – National Research Institute, which holds accreditation No. AB 283. All analyses were performed in accordance with the Polish standard PN-EN ISO/IEC 17025:2005. The accreditation covers all analyzed water quality indicators, which serves as a guarantee of the validity and reliability of the obtained results. The measurement points were located in areas of the Odra River basin, in the Lower Silesian and Opole voivodeships, covering eight groundwater body units (JCWPd) (Fig.1). Most tests were conducted on waters in sandy and sandy-gravel sediments, as well as in limestones, marls, tuffs, and tuffites of both confined and unconfined aquifers (Table 8). A total of 26 locations were used, encompassing 634 groundwater sample measurements. Calculations for the CCME WQI were performed for the years 2009, 2014, 2019, and 2024, while calculations related to water suitability for irrigation (SSP, SAR, KR, MAR, EC indices) were carried out for multi-year periods: 2005–2009, 2010–2014, 2015–2019, and 2020–2024. Particular emphasis was placed on the most recent years (2024 and 2020–2024).

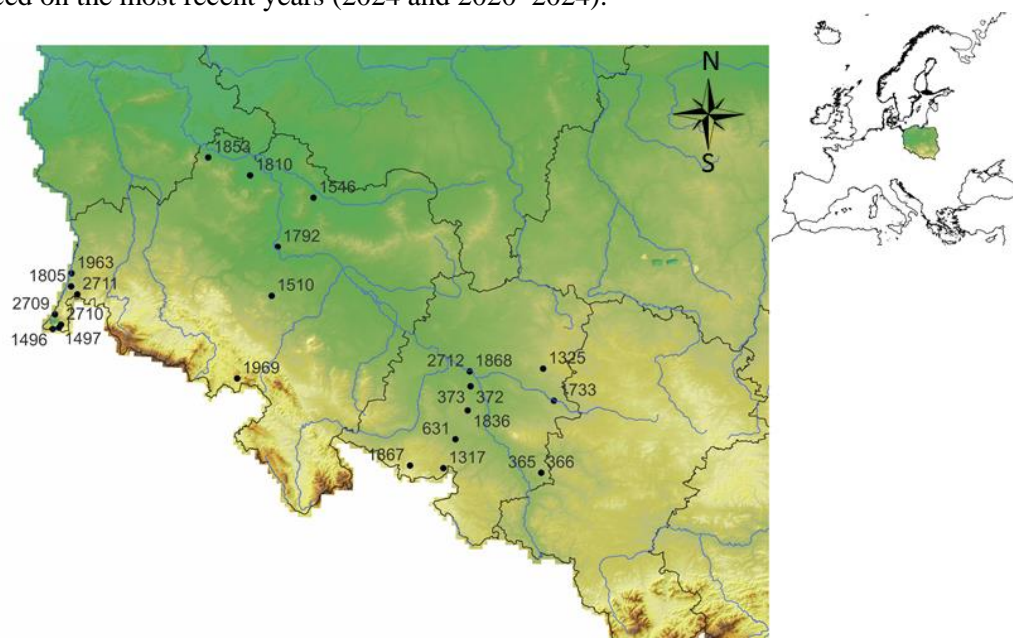


Fig. 1. Location of measurements points (the numbers on the map refer to the monitoring point identifiers as listed in the State Environmental Monitoring database <https://mjwp.gios.gov.pl/>)

Table 8. Hydrogeological characteristics of selected groundwater monitoring points (the numbers on the map refer to the monitoring point identifiers as listed in the State Environmental Monitoring database <https://mjwp.gios.gov.pl/>) (where: UN – unconfined water table, C- confined water table)

ID	Borehole type	Type of water table	X	Y	Elevation (m a.s.l.)	Aquifer bottom (m b.g.l.)	Aquifer top (m b.g.l.)	Stratigraphy	Lithology	Aquifer Type	Voivodeship	Site
1867	drilled well	C	387895.5	274363.4	311	18.1	12	Q	sands+gravels	porous	Opole	Charbielin
1317	drilled well	UC	404400	273066.8	236.5	19	11.1	Q	sands+gravels	porous	Opole	Dytmarów
1963	piezometer	UC	220196.3	369623	184.3	11.6	1.2	Q	gravels+sands	porous	Lower Silesian	Zgorzelec
1805	drilled well	C	220017	363138	210	22.3	15.7	Pg+Ng	gravels+sands	porous	Lower Silesian	Osiek Łużycki
2711	piezometer	C	223076	359230.2	233.7	101	45	Q	gravels+sands	porous	Lower Silesian	Zawidów
2709	drilled well	C	212000.5	349291.9	223.42	20	18.5	Pg+Ng	gravels+sands	porous	Lower Silesian	Bogatynia
2710	piezometer	UC	214979	344161.4	259.55	29	5	Pg+Ng	clay piaszczyste	porous	Lower Silesian	Bogatynia
1733	piezometer	UC	459188.3	306480.1	204.84	19.5	5.73	Q	sands+gravels	porous	Opole	Zawadzkie
631	drilled well	UC	410408.6	287404.5	187	21	5.3	Q	sands	porous	Opole	Łącznik
1325	drilled well	C	453850.3	322374.3	220	14	8.1	T	sandstones	porous-fractured	Opole	Zębowice
1868	piezometer	UC	417485.3	321002.1	148.8	9	1.5	Q	sands medium-grained	porous	Opole	Dobrzeń Mały
2712	piezometer	C	417485.3	321002.1	148.8	44	17	K2	marls	porous-fractured	Opole	Dobrzeń Mały
1969	spring	S	302260.3	317512.9	567.5			P1+2	tuffites+tuffs	porous-fractured	Lower Silesian	Kowalowa
1546	drilled well	C	340065	407088.2	97.6	28	7	Q	sands+gravels	porous	Lower Silesian	Kamień Górski
1810	drilled well	C	308659.3	418159	79	30	24	Q	sands fine-grained	porous	Lower Silesian	Szymocin
1496	piezometer	C	210920.9	342042.4	282.09	21	16	Ng	sands+gravels	porous	Lower Silesian	Białopole
1836	drilled well	UC	416452.6	301693.5	192.03	55	11	Q	sands medium-grained	porous	Opole	Jaśkowice
1497	piezometer	C	213961	342638.6	259.84	45.5	27	Ng	sands+lignite	porous	Lower Silesian	Opolno - Zdrój
1792	drilled well	UC	322342.1	382776.8	122.1	14.2	7	Q	sands varigrained	porous	Lower Silesian	Lubiąż
1853	piezometer	C	287930.4	427037.2	102.75	13.8	9.3	Q	sands+gravels	porous	Lower Silesian	Zameczno
1510	drilled well	C	319362.7	358475.2	165.81	10	2.5	Q	gravels	porous	Lower Silesian	Różana
370	drilled well	UC	417890.7	313652.5	152.5	36	2	Q	sands	porous	Opole	Wrzoski
372	drilled well	C	417871.1	313655.4	152.5	401	302	T2	limestones+dolomites	fractured-karst	Opole	Wrzoski
373	drilled well	C	417884.4	313662.3	152.43	181	169	K2	sandstones	porous-fractured	Opole	Wrzoski
365	drilled well	C	452914.6	270801.7	196.6	88.3	85.5	NgM	sands	porous	Opole	Stara Kuźnia
366	drilled well	UC	452906.7	270801.7	196.7	26	2.4	Q	gravels	porous	Opole	Stara Kuźnia

3. RESULTS

3.1. Results of the drinking water safety assessment

Among all 26 monitoring points analysed in 2009, 2014, 2019, and 2024, none were classified as poor according to the CCME WQI (Fig. 2). In 2024, 42% of the points were classified as marginal, 35% as good, 15% as excellent and 8% as fair.

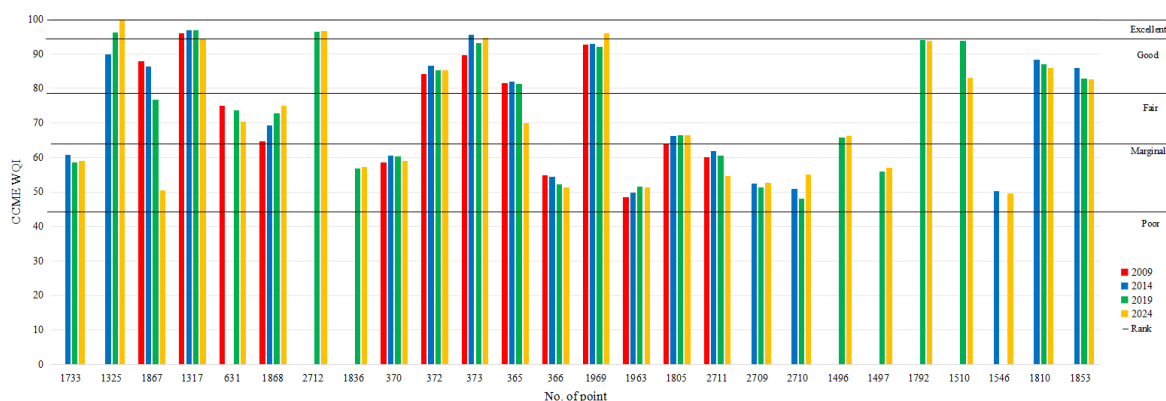


Fig. 2. Classification of monitoring points according to the CCME WQI in 2009, 2014, 2019, and 2024

The analysis of CCME WQI values in 2009, 2014, 2019, and 2024 reveals considerable variability in groundwater quality across the monitoring points (Fig. 2). In a few locations, such as Zębówice (1325), Dobrzeń Mały (1868), Dobrzeń Mały (2712), and Białopole (1496), an increasing trend in the index was observed, indicating an improvement in groundwater quality. These improvements can be attributed to the natural attenuation of pollutants and, in some cases, reduced local agricultural pressure or the modernization of nearby wastewater management systems. Particular attention is drawn to Zębówice (1325), where the index reached 100 in 2024, reflecting excellent water quality in this area.

Conversely, decreasing trends were observed at Charbielin (1867), Łącznik (631), Stara Kuźnia (366), Lubiąż (1792), Różana (1510), Szymocin (1810), and Zameczno (1853), indicating a deterioration of water quality. The decline in quality at these points is likely linked to increasing anthropogenic pressure. The largest decline occurred at Charbielin (1867), where the index dropped from 87.91 in 2009 to 50.47 in 2024. Some locations, including Jaśkowice (1836), Wrzoski (370), Zgorzelec (1963), Bogatynia (2709), Bogatynia (2710), Opolno-Zdrój (1497), and Kamień Górski (1546), were characterised by stable but low index values, remaining within the marginal category.

Particularly important is the analysis of water quality data from measurements conducted in 2024, which demonstrated significant variability in the CCME WQI across locations. The index ranged from 49.62 to 100, with a mean value of 71.46 ± 17.91 and a median of 66.34. The fact that the median is lower than the mean suggests a skewed distribution, where a significant portion of the monitoring points exhibit quality below the average, primarily due to localized high-intensity pollution. The coefficient of variation of 25.06% indicated moderate but notable variability in water quality between monitoring points, suggesting the influence of local environmental and anthropogenic factors.

Correlation analysis between individual physicochemical parameters and the CCME WQI revealed clear patterns (Fig. 3). Iron and manganese were the parameters exerting a negative impact on water quality. Fe showed the strongest negative correlation with CCME WQI ($r = -0.898$). The mean Fe concentration in the analysed samples was $7.63 \text{ mg} \cdot \text{dm}^{-3}$, with a wide range from 0.01 to $22.95 \text{ mg} \cdot \text{dm}^{-3}$.

and median $6.61 \text{ mg}\cdot\text{dm}^{-3}$. Similarly, Mn exhibited a strong negative correlation with CCME WQI ($r = -0.756$), with a mean concentration of $0.45 \text{ mg}\cdot\text{dm}^{-3}$ and a range from 0.001 to $1.944 \text{ mg}\cdot\text{dm}^{-3}$ and median $0.26 \text{ mg}\cdot\text{dm}^{-3}$. The third parameter with a significant negative effect on drinking water quality was ammonium (NH_4^+), showing a correlation of $r = -0.575$. The mean ammonium concentration was $0.36 \text{ mg}\cdot\text{dm}^{-3}$ and median $0.14 \text{ mg}\cdot\text{dm}^{-3}$, but it was characterised by very high variability, with a coefficient of variation of 124.42%. These results indicate a significant influence of iron, manganese, and organic nitrogen compounds on the deterioration of water quality at the monitored sites. The deterioration of water quality caused by Fe and Mn is often related to the redox conditions within the aquifer. Under anaerobic conditions, these metals dissolve from the geological matrix into the groundwater. Ammonium (NH_4^+) in these areas likely originates from both natural decomposition of organic matter in the soil and anthropogenic sources such as nitrogen-based fertilizers. To mitigate this degradation, management measures should include the establishment of source protection zones, the implementation of controlled fertilization plans, and, at the consumer level, the use of advanced oxidation and filtration systems (e.g., aeration followed by sand filtration) to remove excess metals.

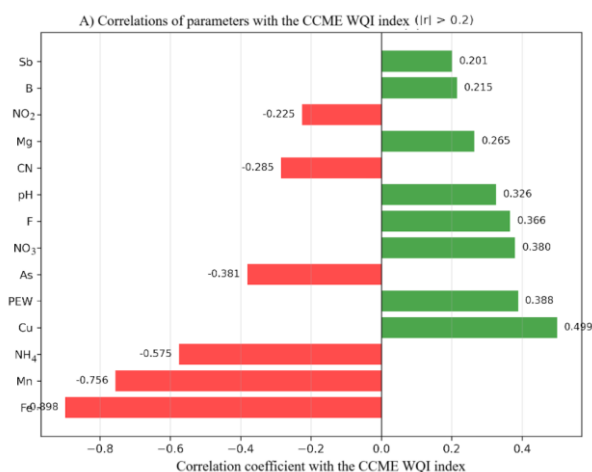


Fig. 3. Correlation of input parameters with the CCME WQI

The analysis of individual parameter variability for 2024 revealed significant differences between monitoring points. The highest variability was observed for nitrates (NO_3^-), with a coefficient of variation of 268.09% and a concentration range of 0.06 to $177.5 \text{ mg}\cdot\text{dm}^{-3}$, median $0.16 \text{ mg}\cdot\text{dm}^{-3}$, indicating highly diverse sources of this component across different sampling points. Similarly high variability was found for nickel ($\text{CV} = 249.96\%$) and boron ($\text{CV} = 159.59\%$). In contrast, some components exhibited complete stability in the analysed samples, including chromium (Cr), selenium (Se), and silver (Ag), which remained constant across all monitoring points. Particular attention is drawn to the stability of pH in the analysed samples. This relative stability of pH indicates good buffering capacity of the studied waters and the absence of significant acidifying or alkalisating sources in the study area. The substantial variability of some analysed parameters highlights the heterogeneity of the study area in terms of pollution sources and processes affecting water quality. This variability suggests the need for a site-specific approach to groundwater quality management for drinking purposes and the identification of specific pollution sources at each location.

In 2024, the largest share of cases corresponded to observation points classified as marginal water quality ($\sim 42\%$). The highest exceedances were observed for pH, NH_4^+ , NO_3^- , Mg, Mn, and Fe. Single

instances of As and SO_4^{2-} exceedances were also noted. Among all locations, point 1325 (Zębowice, Opole Voivodeship) stood out, showing the maximum index value of 100. Conversely, the lowest CCME WQI value was recorded at point 1546 (Kamień Górowski, Lower Silesian Voivodeship). Exceedances were observed for Fe, Mn, and NH_4^+ . For Fe, exceedances reached up to tenfold relative to the applicable standard. Excess iron in the human body can have serious health consequences, damaging proteins, lipids, DNA, and cell membranes. It can also contribute to cancer, skin discoloration, and metabolic disorders (Stawarz-Janeczek et al. 2024).

Manganese exceeded the limit by approximately 40-fold. Excess manganese in groundwater causes a metallic taste, discoloration, and deposits in water supply systems, increasing infrastructure maintenance costs (Kaleja et al. 2006). High manganese concentrations may also indicate pollution or anoxic conditions in aquifers, promoting the growth of iron- and manganese-oxidising bacteria, which further deteriorates water quality (Nawrocki 2010). From a health perspective, excess manganese can affect the nervous system, causing Parkinson's-like symptoms, especially during long-term exposure (World Health Organization 2022).

Ammonium toxicity results from its ability to cross the blood–brain barrier, leading to central nervous system damage. Symptoms of excessive NH_4^+ include disorientation, drowsiness, and convulsions. In extreme cases, it can cause hepatic coma or death. In children, symptoms may include muscle hypotonia, loss of appetite, and hyperventilation (World Health Organization 2022). The median NH_4^+ concentration was $0.14 \text{ mg}\cdot\text{dm}^{-3}$, highlighting the skewed distribution caused by elevated values at a limited number of points.

3.2. Water suitability for irrigation

The assessment of groundwater for agricultural use is crucial for ensuring soil health and crop productivity. In the study area, the majority of points maintained high suitability, but localized issues with salinity and sodicity were observed.

The distribution of data points on the Piper diagram (Fig. 4) indicates a clear predominance of the calcium-bicarbonate water type, which is characteristic of natural water circulation systems in the sedimentary rocks of south-western Poland. The slight dispersion of some points toward the sulfate and chloride fields area may reflect the influence of local anthropogenic factors or geochemical processes occurring within the studied aquifers over the analyzed long-term period.

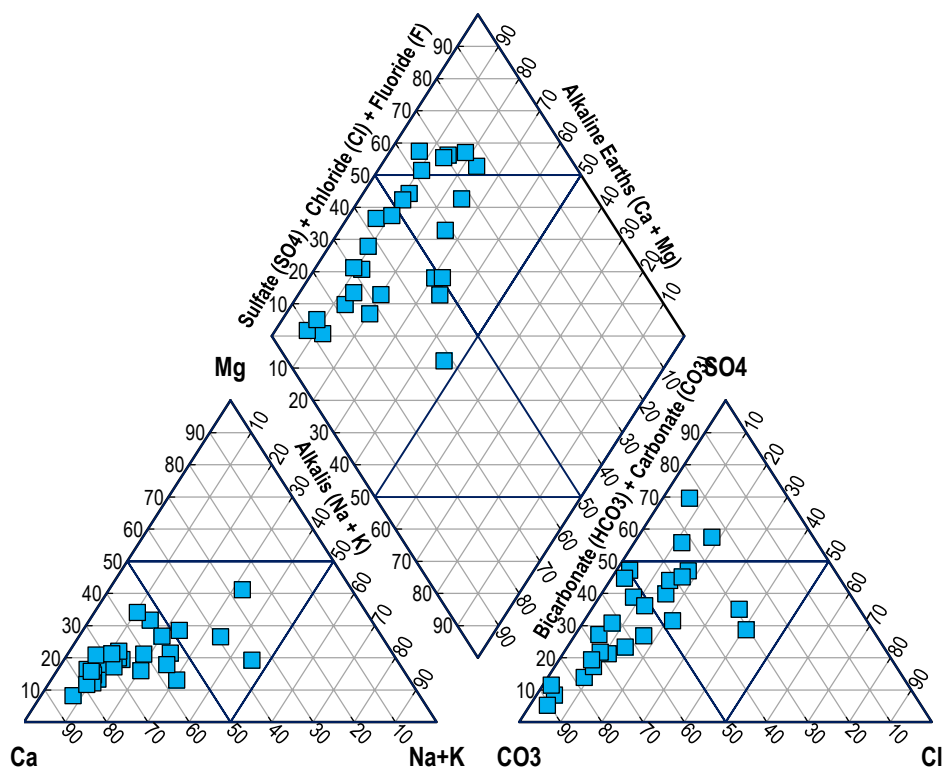
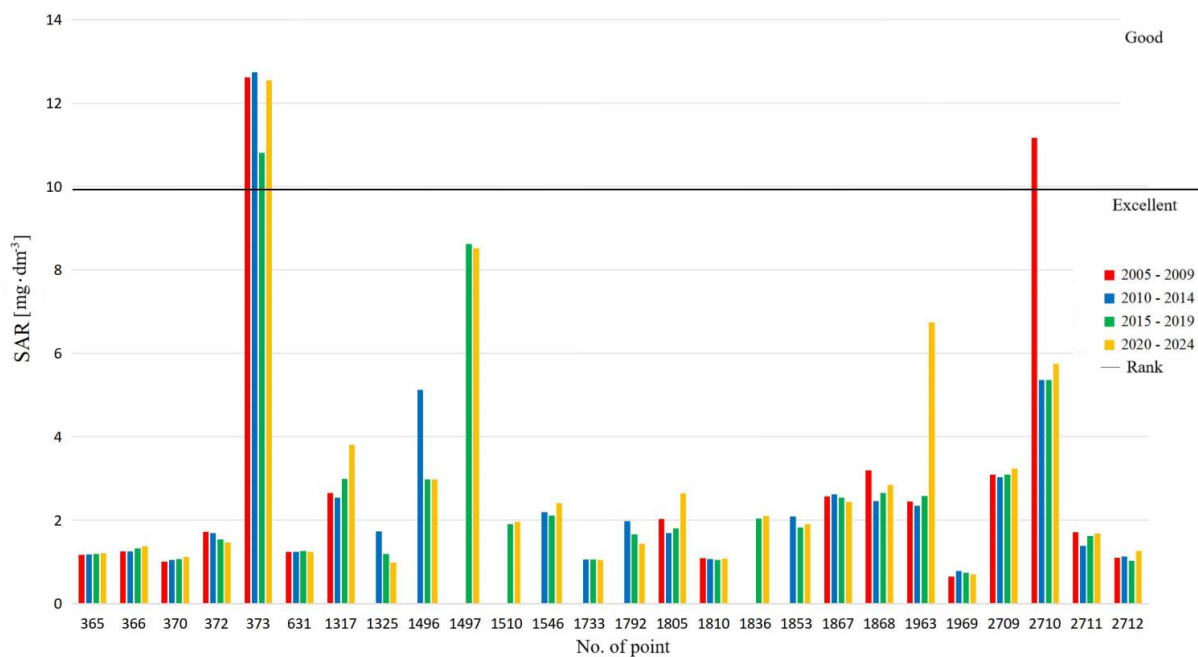
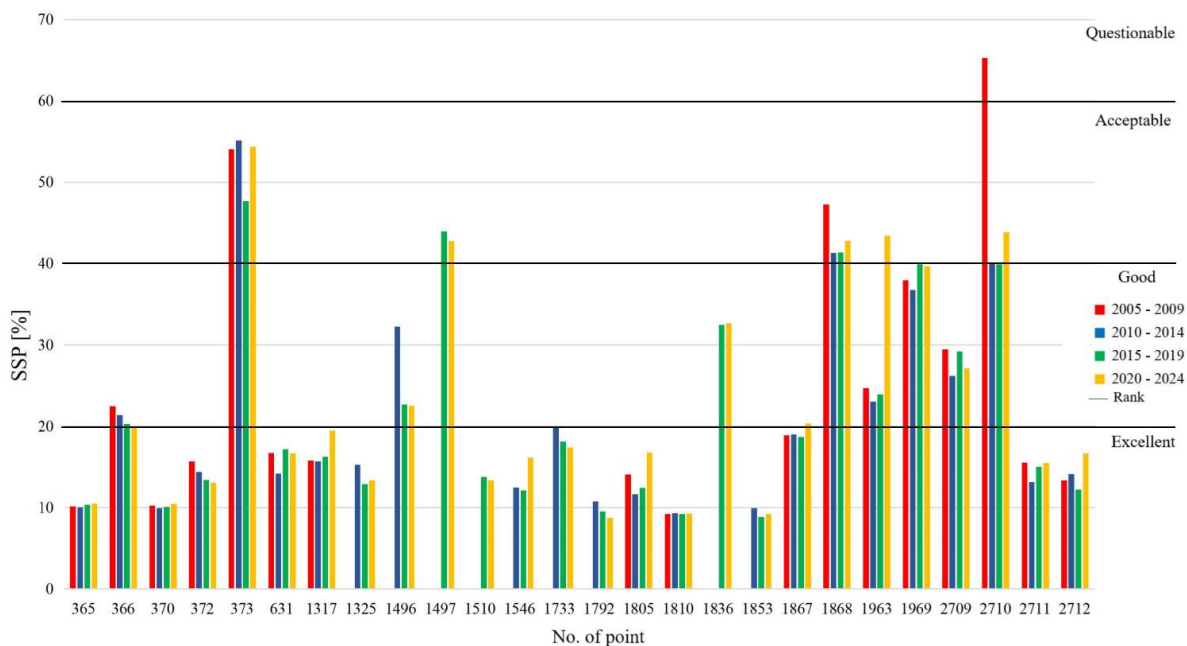
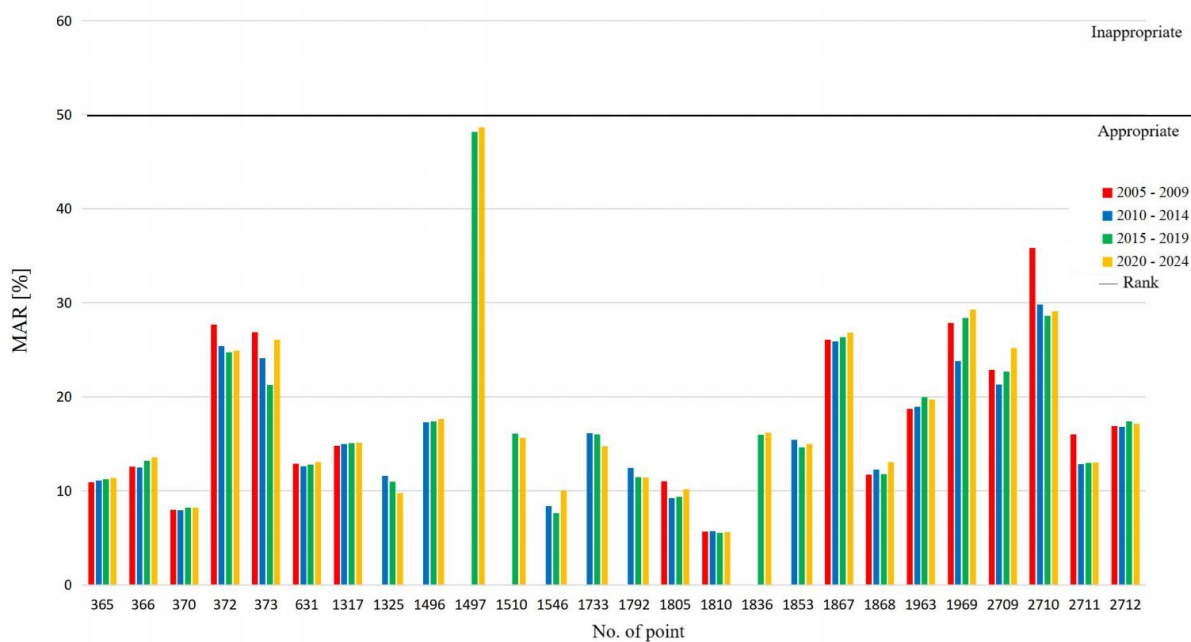
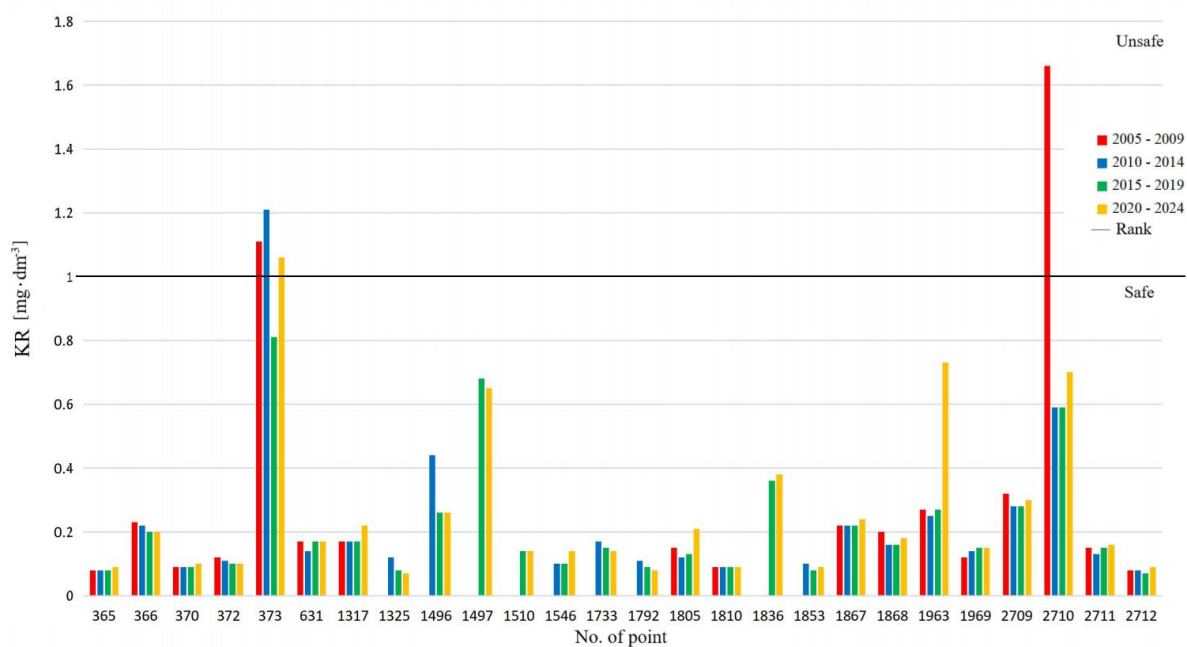


Fig. 4. Piper diagram illustrating hydrochemical types of the studied waters

The results of the analysis of water suitability for irrigation are presented in Fig. 5. The SSP index showed excellent quality at 15 stations across all multi-year periods, good quality at 5 stations, and permissible quality at 3 stations (points: 1868 in Dobrzeń Mały, 373 in Wrzoski, Opole Voivodeship; 1497 in Opolno-Zdrój, Lower Silesian Voivodeship). In the most recent period (2020–2024), two stations exhibited a decline in class: point 1867 (Chrabielin, Opole Voivodeship) from excellent to good, and point 1963 (Zgorzelec, Lower Silesian Voivodeship) from good to permissible. Point 2710 (Bogatynia, Lower Silesian Voivodeship) had a doubtful class in the first period, good in the next two, and permissible in the last period. These changes are associated with the upward migration of deeper, more mineralized waters or the cumulative effect of long-term agricultural runoff.

The SAR index showed excellent quality at 24 stations across all multi-year periods, except for point 373 (Wrzoski, Opole Voivodeship), which was classified as good. At point 2710 (Bogatynia), the class was good in the first period and excellent in subsequent periods. The KR index maintained a safe quality class at 24 stations throughout all periods. Exceptions were point 373 (Wrzoski, Opole Voivodeship), which had a safe class in 2015–2019, and point 2710 (Bogatynia), which was classified as unsafe in the first period and safe in subsequent periods. The MAR index reached a safe quality class at all stations across all periods. EC showed low impact on soil and plants at 4 stations (1733 in Zawadzkie, 1836 in Jaśkowice, 366 in Stara Kuźnia, Opole Voivodeship; 1969 in Kowalowa, Lower Silesian Voivodeship), medium impact at 16 stations, and high impact at 3 stations (1792 in Lubiąż, 1546 in Kamień Górski, 1853 in Zameczno, Lower Silesian Voivodeship). At point 1317 (Dytmarów, Opole Voivodeship), the impact was medium in 2010–2014 and high in other periods. At point 631 (Łącznik, Opole Voivodeship), the impact was medium in 2010–2014 and low in other periods.





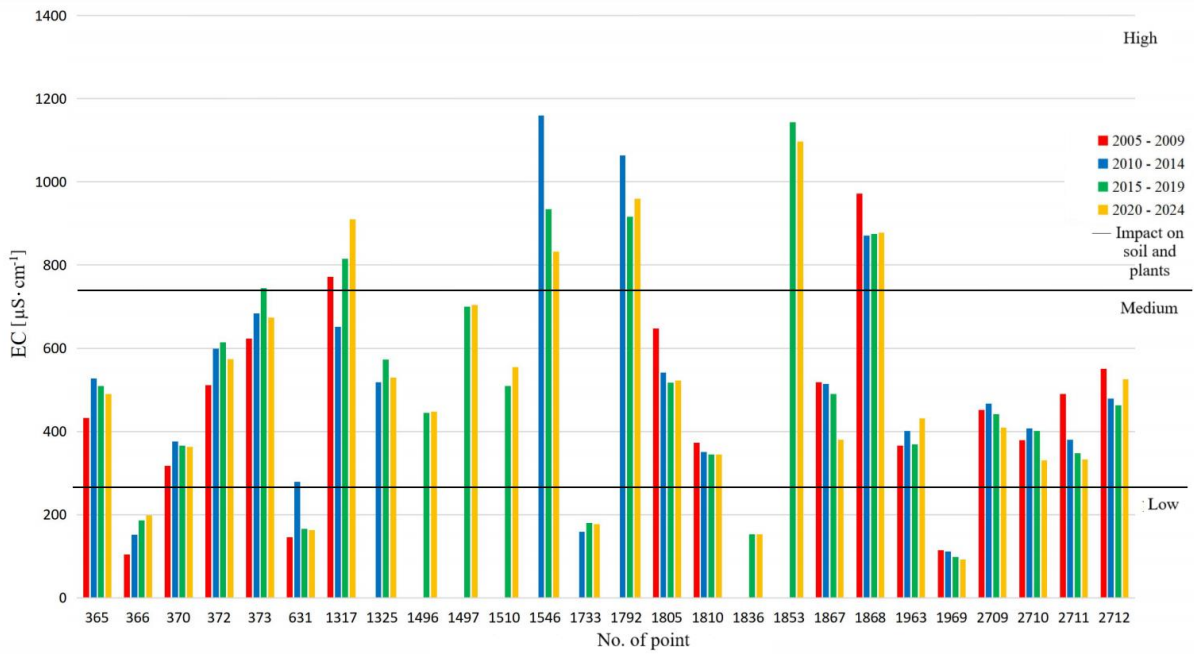


Fig. 5. Characteristics of groundwater salinity indices at the analyzed monitoring points in the multi-year periods 2005–2009, 2010–2014, 2015–2019, and 2020–2024

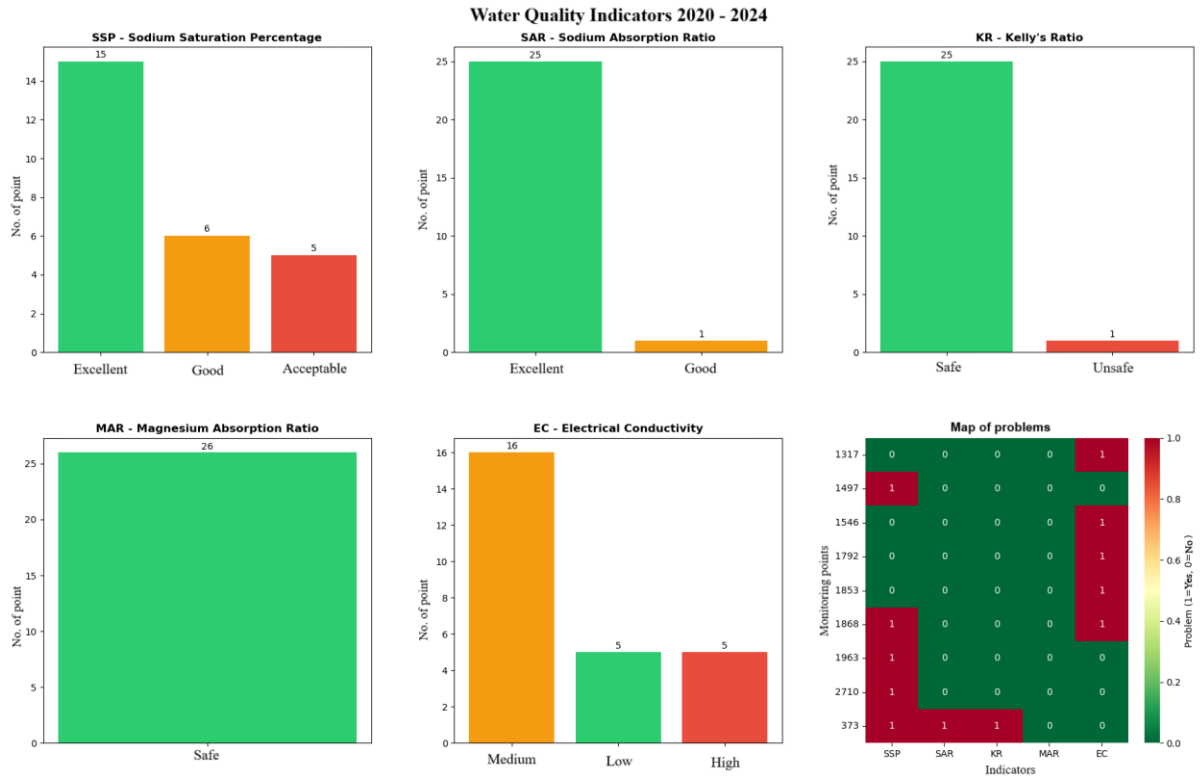


Fig. 6. Comprehensive analysis of water quality indicators

Fig. 6 presents a comprehensive analysis of groundwater quality indices based on the most recent data (2020–2024). Key findings from the charts include the following: the SSP index indicates that the majority of points (21) exhibit excellent quality, although 5 points show a concerning ‘permissible’ level. The SAR index generally shows good quality, with 25 points classified as excellent and only 1 point (373) as ‘good’. For the KR index, most points (25) fall within the safe category, with the exception of point 373. The MAR index shows that all samples are at a safe level. Electrolytic conductivity (EC), however, produces mixed results: 16 points show medium values, 5 points low, and 5 points high conductivity. High EC values at points such as 1546 and 1853 suggest a risk of soil salinization if these waters are used continuously for irrigation without adequate drainage. The heat map clearly highlights point 373 in Wrzoski, Opole Voivodeship, as the most problematic, showing issues across three indices (SSP, SAR, and KR), requiring immediate attention and intervention. Other concerning points include 1868, 1963, 2710, and 1497, which show issues with SSP, and points 1317, 1792, 1546, and 1853, where high EC values were recorded. These observations underline the need for ongoing monitoring and remedial actions.

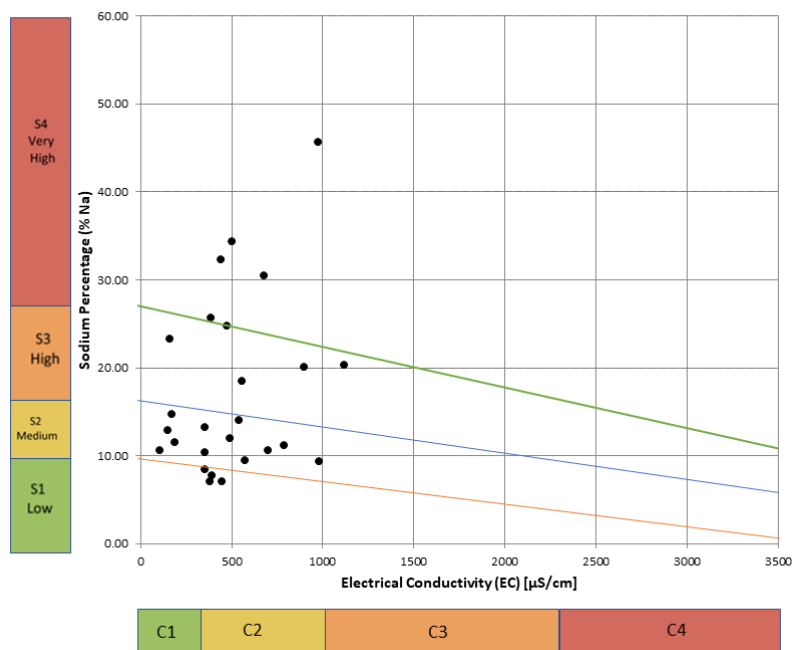


Fig. 7. Wilcox diagram for the classification of irrigation water quality

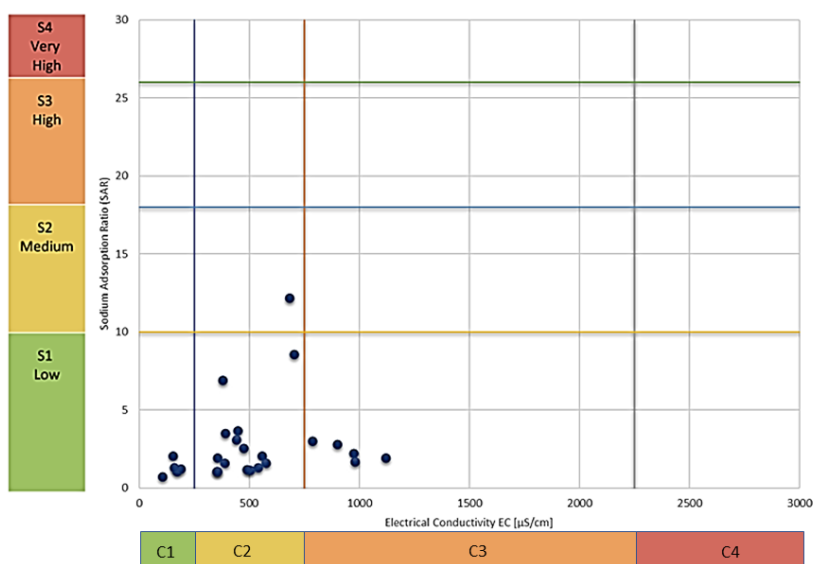


Fig. 8. USSL diagram for the classification of irrigation water quality

In order to complement the information and evaluate the suitability of the studied groundwater for irrigation, two complementary classification methods were employed: the Wilcox diagram and the USSSL (U.S. Salinity Laboratory) diagram. The Wilcox diagram classifies water based on sodium percentage (% Na) and total salinity (EC), providing a practical view of the water's impact on crops. The USSSL diagram, integrating Sodium Adsorption Ratio (SAR) and EC, offers a more detailed assessment of the sodium hazard by considering the counterbalancing effect of calcium and magnesium. The distribution of the groundwater samples on the Wilcox diagram (Fig. 7) indicates generally very high quality. The vast majority of the samples fell within the 'Excellent to Good' category. These points show low salinity ($EC < 250 \mu\text{S/cm}$) and a very low sodium hazard (% Na $< 20\%$). A smaller group of points is located in the 'Good to Permissible' zone, with slightly higher salinity ($EC 250-750 \mu\text{S/cm}$) but still low sodium (% Na 20-40%). This indicates that the water is generally suitable for most crops. This positive assessment is further reinforced by the USSSL diagram (Fig. 8). Almost all samples belong to the C1-S1 class, signifying low salinity and low sodium hazard. This water is excellent for most crops on most soils without special management. A few points are classified as C2-S1 (moderate salinity, low sodium hazard), which is also considered good quality water suitable for irrigation. The C2-S1 water is appropriate for moderately tolerant plants but may require occasional leaching of salts from the soil, especially on poorly drained soils. The high cluster in the C1-S1 zone (lowest EC, lowest SAR) represents the most widespread water type in the study area, indicating minimal risk of soil salinity or alkalization.

3.3. Spatial analysis

Spatial analysis (Fig. 9) of CCME WQI data from the most recent year highlights a concentration of marginal-quality points in the western part of the study area. This location also shows the greatest variability in SSP. Electrical conductivity (EC) in western areas remains in the 'medium' category. In contrast, the south-eastern and central parts of the study area show variability ranging from 'low' through 'medium' to 'high' classification.

The spatial patterns demonstrate that the western region is more susceptible to quality degradation, likely due to a combination of geological vulnerability and more intensive land use.

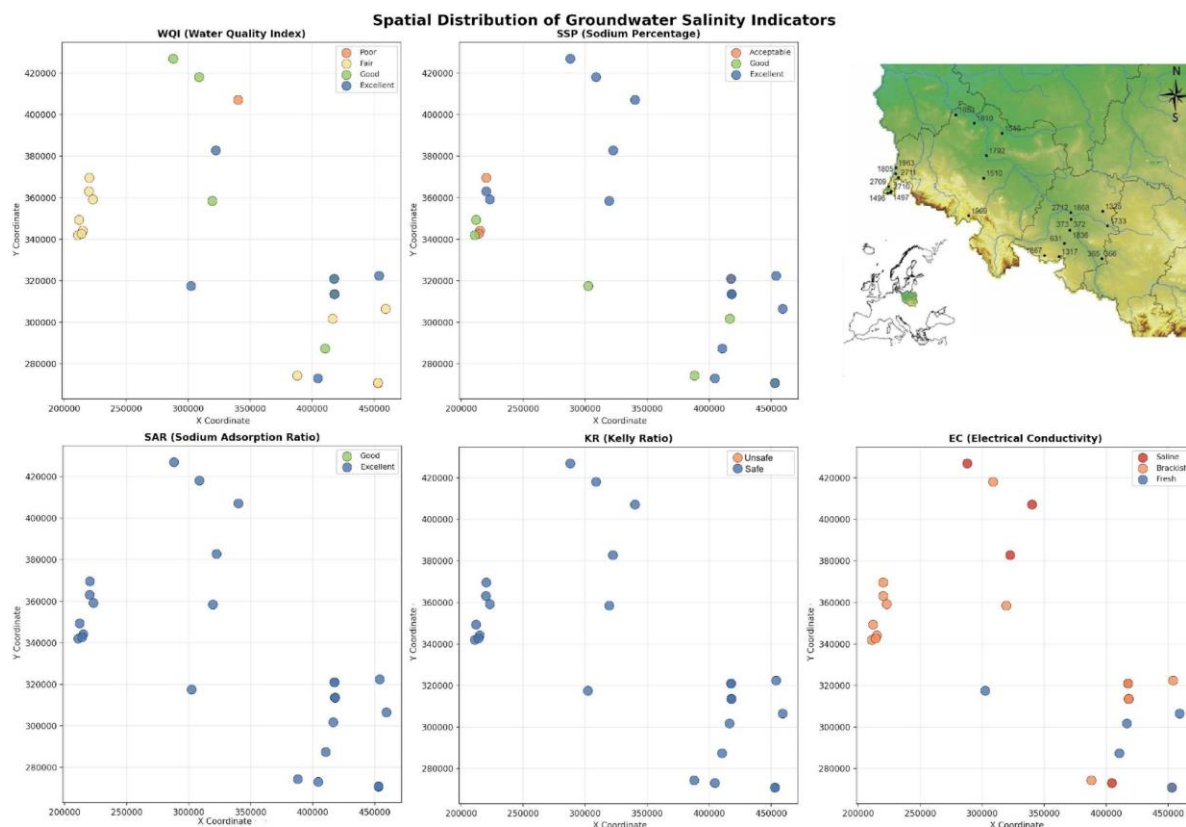


Fig. 9. Spatial variability of the analyzed indices

4. DISCUSSION

The analysis of the CCME WQI index for the years 2009, 2014, 2019, and 2024 revealed significant variability in groundwater quality, consistent with studies on the influence of local geological and anthropogenic factors on groundwater (Monitoring wód podziemnych 2024). Spatial analysis indicates a concentration of marginal-quality points in the western part of the study area, which may be associated with higher anthropogenic pressure (development of extractive industries) in this part of the Lower Silesian Voivodeship. The observed changes in water quality at individual points are driven by two main factors: the systematic intensification of agricultural runoff in certain areas (leading to quality deterioration) and, conversely, the modernization of local wastewater infrastructure, which explains the localized improvements in the index.

Strong negative correlations between CCME WQI and concentrations of iron, manganese, and ammonium show dependencies indicating that these parameters are the main factors deteriorating groundwater quality, in line with previous studies (Michałkiewicz and Mądrecka 2014). High nitrate variability indicates diverse pollution sources, such as agricultural fertilisation or sewage infiltration, consistent with observations in other regions of Poland (Górski 2022; Walczak 2018). The significance of these exceedances is critical, as they not only limit the direct use of water but also indicate a high vulnerability of the studied aquifers to surface-derived pollutants.

High concentrations of iron and manganese, especially at Kamień Górski (1546), where tenfold exceedances for Fe and fortyfold for Mn were recorded, have both technical (e.g., deposits in water supply systems) and health implications (neurotoxicity of manganese) (Maziarka, Krogulska, 2018; Kondraciuk and Łukawski 2023). Ammonium poses a health risk, particularly in points with elevated concentrations, due to its neurotoxicity (Skowrońska 2012). . These results indicate the necessity of implementing specific water treatment technologies prior to domestic use (Wolska et al. 2023; Kaleja et al. 2006). Exceedances of As and SO_4^{2-} at individual points suggest the need for ongoing monitoring to identify their sources. Regarding point 1546 (Kamień Górski), based on available data, the water from this intake exceeds permissible limits for Fe and Mn, raising serious concerns about its use for drinking purposes without prior treatment. This specific point is a drilled well, groundwater from the Quaternary aquifer level is commonly utilized by local residents for water supply (Rada Miejska Wąsosza 2014). Long-term trend analysis at this site shows that the exceedances are not incidental but represent a persistent pattern of quality, likely driven by natural geochemical processes (reducing conditions in the aquifer, dissolution of Fe/Mn-bearing minerals) potentially exacerbated by anthropogenic pressures. Recommended are remedial measures.

The SSP, SAR, KR, MAR, and EC indices indicate generally good suitability of the waters for irrigation, consistent with studies on groundwater in agricultural regions of Poland (Wąsik 2011) . Issues with water quality and its use for various purposes at points such as Wrzoski (373) or Bogatynia (2710) have been reported by other authors (Kubicz et al. 2018, 2021; Rak and Landwójtowicz 2014).

The JCWPD area No. 105, where point 2710 (Bogatynia) is located, is influenced by intensive lignite surface mining (open-pit extraction), which significantly alters local hydrogeological conditions, as well as intensive agricultural activities, with only small forested areas. Consequently, agricultural pollutants, such as fertilisers and plant protection products, pose a risk due to the poor protection of the main usable aquifer. Considering the low thickness of low-permeability formations limiting groundwater protection from the surface, the depth of groundwater intakes, terrain morphology, and groundwater flow direction, JCWPD No. 105 can be classified as highly vulnerable to pollution (Państwowy Instytut Geologiczny 2023). An individual approach to water quality management at each location is crucial for sustainable water resource use.

The study presented in this article serves as an introduction to broader analyses of groundwater use from various aquifer levels and under differing geological and anthropogenic conditions. Expanding the number of sampling points and considering aquifer characteristics will provide more representative data. The high variability of certain parameters highlights the need for detailed studies on pollution sources, including the impact of agriculture, industry, and urbanisation, and the consequences of their presence in groundwater regarding its potential uses.

5. CONCLUSIONS

The results of this study lead to the following synthetic conclusions, which emphasize the practical aspects of groundwater resource management in the Odra River basin.

Groundwater quality for drinking purposes is primarily shaped by a dualism of factors, stable geogenic conditions (responsible for persistent Fe and Mn exceedances) and dynamic anthropogenic pressures (influencing nitrogen and trace element variability). This distinction is crucial for management, as geogenic issues require permanent technical solutions (water purification), while anthropogenic impacts necessitate land-use policy interventions.

The high variability of nitrates, nickel, and boron serves as a direct indicator of localized environmental vulnerability. The significant exceedances of these parameters suggest that current

protective measures in areas of intensive agriculture and industrial activity are insufficient, requiring a revision of local groundwater protection zones.

The case of Kamień Górowski (1546) and similar locations highlights a significant public health implication. The stability of poor water quality at these points indicates that without specialistic water purification these resources remain unfit for safe human consumption, despite their potential availability.

While the suitability of groundwater for irrigation remains generally high, the localized increase in electrical conductivity (EC) and sodium-based indices (SSP) should be interpreted as an early warning signal. For agricultural practice, this implies a risk of long-term soil structure degradation (salinization), which may require a shift toward more sustainable irrigation scheduling or the mixing of groundwater with surface water.

The observed temporal trends, ranging from significant improvement (Zębowice) to severe deterioration (Charbielin), underscore the necessity of a "risk-based" monitoring approach. Future management strategies should prioritize high-frequency monitoring at points showing declining trends to identify the exact moment of contamination breakthrough and implement immediate remedial actions.

In conclusion, the effective protection of groundwater in the study area requires an individualized management approach for each location. This must integrate hydrogeological characteristics with specific local contamination sources to ensure both public health safety and the long-term sustainability of agricultural production.

ADDITIONAL INFORMATION

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