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Water pollution hotspots and the role of riparian vegetation in industrial area

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Highlights
- Industrial areas cause salinisation of river water.
- Point-source wastewater discharges are hot spots for water deterioration.
- Riparian vegetation is crucial in reducing N, P, and C compounds in rivers.

Abstract: With the ongoing expansion of urban areas globally, industrial zones are increasingly integrated into city landscapes. These zones, characterised by a high density of industrial facilities from diverse sectors, can pose significant threats to the natural environment, particularly to aquatic ecosystems. This study aims to assess the influence of an urban area containing a designated industrial zone on spatio-temporal variations in river water chemistry and to identify critical zones of water quality degradation. The research was conducted on the Drwinka River, located in Niepołomice, southern Poland.

Findings revealed abrupt shifts in water chemistry along the river, primarily driven by point-source wastewater discharges. Industrial activity led to a marked increase in water salinity, largely due to elevated concentrations of sodium chloride (NaCl). Additionally, wastewater introduced organic and inorganic forms of nitrogen, phosphorus, and carbon into the river, though the negative effects of these pollutants diminished downstream. This attenuation was attributed to the buffering capacity of riparian vegetation, particularly aquatic plants (hydrophytes). Seasonal changes in catchment biological activity also had a significant impact on the concentrations of biogenic elements in the river water.

Overall, the study underscores the importance of riparian zones in mitigating pollution and highlights the need for careful monitoring and management of industrial discharges within urbanised catchments.

Keywords: anthropopressure, biogenic compounds, hydrophytes, salinisation, seasonal variability

INTRODUCTION

According to data from the United Nations (2019), approximately 56% of the world's population currently resides in cities, and by 2050, this percentage is expected to increase to around 68%, reaching approximately 7 billion people. In addition to the growing urban population, cities are also expanding in terms of area. New districts, residential developments, and infrastructure are being established. As cities grow, the demand for spaces to conduct industrial activities also increases. Consequently, many cities worldwide are creating large industrial zones, often in the form of so-called special economic zones, which offer favourable conditions for business operations, such as tax incentives and lower labour costs, supporting industrial development and attracting investments.

Urbanisation is associated with the intensification of human activities, which increase ecological risks and negatively impact the environment (Zhai *et al.*, 2020). Numerous studies indicate that urbanisation leads to a reduction in biodiversity (Piano *et al.*, 2020; Banaszak-Cibicka and Dylewski, 2021) due to the loss of natural habitats and changes in ecosystem structures (Hu, Zhang and Li, 2022), air pollution (Liang and Gong, 2020), increased noise levels (Ulloa *et al.*, 2021), landscape fragmentation (Xu *et al.*, 2018), and changes in aquatic environments (Strokal *et al.*, 2021, Krodkiewska, Spyra and Cieplok, 2022). Industrial zones, in particular, have an intense and negative impact on the natural environment as they often concentrate diverse branches of industry within a confined area. The presence of industrial zones in cities significantly alters the water chemistry of nearby water bodies.

Industrial zones contribute to the deterioration of water quality by introducing various chemical pollutants. For example, studies have shown elevated concentrations of nitrogen and phosphorus compounds, such as ammonia-nitrogen, phosphates, and total suspended solids, in downstream sections of rivers near industrial zones (Glińska-Lewczuk *et al.*, 2016; Jolejole, Cayetano and Magbanua, 2021). Nevertheless, elevated concentrations of biogenic compounds in river waters also originate from agriculture. For example, studies by Brysiewicz *et al.* (2019) indicate increased concentrations of N and P compounds in small agricultural catchments in central and northwestern Poland, as a result of the dumping of fertiliser compounds. Additionally, high concentrations of heavy metals such as chromium (Cr) and cadmium (Cd) have been detected in water and sediments, significantly impacting aquatic environments (Li *et al.*, 2023). Research on the Kor River indicates that the presence of various industrial facilities, such as petrochemical plants, tanneries and coal mines, significantly increases the concentrations of heavy metals (Cd, Cr, Cu, Mo, As, and Ni) in the water (Guéguen *et al.*, 2004; Mokarram, Saber and Sheykhi, 2020). Industrial activity also leads to microbiological contamination, which poses a long-term threat to water sources. For instance, the Zenne River in Brussels exhibited high levels of faecal contamination in its downstream sections below wastewater treatment plants, while combined sewer overflows in the river's catchment were responsible for a significant increase in *Escherichia coli* and enterococci in the water during rainfall events (Ouattara *et al.*, 2014). Studies by Lenart-Boroń *et al.* (2016) also indicate that wastewater treatment plant discharges negatively impact water quality, especially in terms of microbiological contamination. In the studied Białka River, an increase in the number of *E. coli* bacteria was observed as a result of wastewater treatment plant discharges. Significant spatial differences in water quality can also be observed in industrial areas, with downstream sites generally exhibiting poorer water quality compared to upstream sites. This is due to the accumulation of pollutants as water flows through industrial zones (Liu, Shen and Chen, 2018). Nowadays, environmental awareness is growing, along with efforts to improve the state of the natural environment, including the quality of surface waters. Water pollution poses a significant challenge for both ecosystems and water management, which is why increasing emphasis is placed on implementing solutions that can positively impact water chemistry and mitigate its deterioration. One of the key approaches is the development of blue-green infrastructure, which helps reduce pollutants flowing into rivers and lakes, improves water retention, and enhances biodiversity (Dudzińska, Dawidowicz and Gross, 2023). Research clearly confirms that riparian vegetation plays a crucial role in bioremediation, i.e., the natural purification of water. Vegetation zones along rivers, lakes, and wetlands act as natural filters, capturing and neutralising pollutants before they enter surface waters (Trałka, Błachowicz and Jakubiak, 2023). Hydrophytic plants play a particularly important role in this process, as they effectively absorb excess nutrients such as N and P originating from agricultural and industrial activities (Milke, Gałczyńska and Wróbel, 2020). Additionally, vegetation reduces the amount of suspended solids in the water by trapping soil particles and sediments from erosion. This leads to improved water clarity, which is crucial for aquatic organisms, especially submerged plants that require access to sunlight. Moreover, vegetation zones serve a stabilising function – their roots strengthen riverbanks and lake shores, reducing erosion and limiting the silting of riverbeds (Camporeale *et al.*, 2013).

Research on water quality and chemistry in industrial zones is extremely important as it allows us to understand the impact of industrial activity on aquatic environments in areas where many facilities from various industrial sectors operate in relatively small spaces. These specific areas, characterised by intense economic activity, are found worldwide. Water pollution in industrial zones is a problem observed in various parts of the globe. Moreover, water quality issues caused by industrial activities can spread beyond local industrial zones, affecting water resources on a larger spatial scale. By analysing specific cases and developing effective mitigation measures in one region, it is possible to create universal strategies that can be applied in other areas to prevent environmental degradation on a broader scale.

The aims of the study are:

1) to determine the impact of an urban area with a special industrial zone on the spatio-temporal changes in water chemistry along the river course,
2) to identify the factors and hotspots where water quality deteriorates or improves along the river course.

STUDY MATERIALS AND METHODS

RESEARCH AREA

The study was conducted in the upper section of the Drwinka River, a right tributary of the Vistula River located in southern Poland (Fig. 1). The investigated catchment area of the Drwinka River covers 17 km^2. Land use in the catchment is dominated by industrial areas 51%, with grasslands covering 36%, forests occupying 13%, and service-residential buildings making up 10% of the area. Administratively, the studied catchment is located in Niepołomice. The Niepołomice municipality is one of the fastest-growing municipalities in Poland. Due to its favourable location, good transportation accessibility, and developed infrastructure, the city has become an investment destination for more than 80 large companies within the Special Economic Zone-Niepołomice Investment Zone (Pawlak, 2019). The zone covers an area of 542 ha and hosts major enterprises primarily from the automotive, logistics, food, and machinery industries. In addition to large industrial plants, according to data from Statistics Poland in 2023, approximately 4,500 other businesses, mainly in the service sector, operate in the Niepołomice municipality (GUS, no date). The study was conducted at 11 measurement points located along the course of the Drwinka River and at 2 wastewater inflow sites (sites 4 and 9) from the industrial zone.

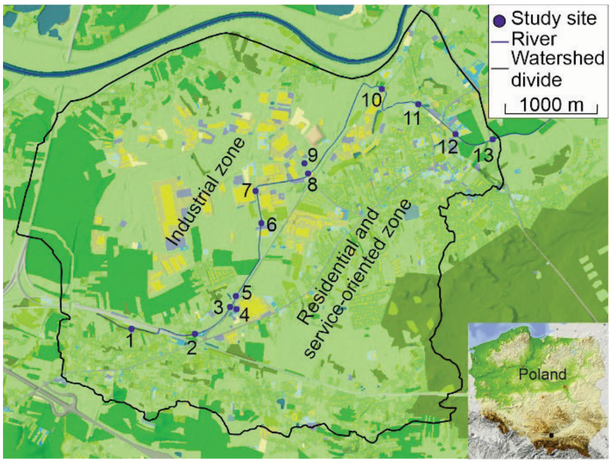

Fig. 1. Study area and localisation of study sites; source: own study

FIELD STUDY AND LABORATORY ANALYSIS

The research was conducted monthly in 2023–2024, with a total of 24 measurement series carried out. In the field, basic physicochemical parameters of the water were measured using a handheld WTW Multi 3630 IDS meter, including water temperature (*T*), pH, electrical conductivity (*EC*), concentration of dissolved oxygen (*DO*) and oxygen saturation (*DO%*). Water samples were collected in sterile 0.5-liter polyethylene bottles for laboratory analyses to determine their chemical composition. Before analysis, the water samples were filtered through a 0.45 μm pore-size membrane to remove suspended solids and particulates. The chemical composition of the water was analysed using ion chromatography. A DIONEX 2000 ion chromatograph with AS-4 autosampler was used for the chemical analysis. Fourteen ions were identified in the water samples, including major ions (Ca^{2+}, Mg^{2+}, Na^+, K^+, HCO_3^-, SO_4^{2-}, Cl^-), nitrogen and phosphorus compounds (NH_4^+, NO^{3-}, NO_2^-, PO_4^{3-}), and trace elements (Li^+, Br^-, F^-). Water mineralisation (TDS) was calculated as the sum of the determined ions. A Vario TOC CUBE analyser with interchangeable carousels for automated liquid sample collection was used to measure total organic carbon (*TOC*), inorganic carbon (*TIC*), total carbon (*TC*), and total nitrogen (*TN*). Additionally, the concentration of organic nitrogen was calculated as the difference between total nitrogen (*TN*) and inorganic nitrogen (*TIN*). The dissolved oxygen deficit (*DO* deficit) was also calculated. The method and accuracy of chemical analyses were carried out in accordance with the standards: PN-EN ISO 14911 (Polski Komitet Normalizacyjny, 2002), PN-EN ISO 10304-1 (Polski Komitet Normalizacyjny, 2009), and PN-89 C-04638/02 (Polski Komitet Normalizacyjny, 1990).

STATISTICAL ANALYSIS

The study employed ANOVA analysis and Scheffé post-hoc test (p = 0.05) to determine the occurrence of seasonal changes in water chemistry. Pearson's linear correlation coefficients (p = 0.05) were calculated between physicochemical parameters of the water. To identify the factors shaping water chemistry in the Drwinka River catchment, Principal Component Analysis (PCA) was used. The Kaiser criterion was applied to select the principal factors. Statistical analyses were conducted using the STATISTICA 13 software.

RESULTS AND DISCUSSION

CONTENT AND SEASONAL CHANGES OF SELECTED PHYSICO-CHEMICAL PARAMETERS IN WATER

The values of river water quality parameters depend on various factors and processes occurring on temporal and spatial scales. The basic statistics of the physico-chemical parameters of the studied waters in the Drwinka River catchment are presented in Table 1. The average water temperature was 10.6°C, the pH was slightly alkaline at 7.68, and the conductivity measured *EC* = 1251 $\mu S \cdot cm^{-1}$. Among the cations, the highest average concentration was found for Na^+ ions, while among the anions, HCO_3^- had the highest average concentration. Among the analysed trace elements, F^- ions had the highest average concentrations, while Br^- ions had the lowest, with concentrations in all samples below the detection limit; therefore, they were not included in Table 1.

Table 1. Basic statistics of the physico-chemical parameters of water in the Drwinka catchment

Parameter	Unit	Mean	Min.	Max.	*CV* (%)
T	°C	10.6	1.0	26.2	49.3
pH	–	7.68	6.57	8.6	5.3
EC	$\mu S \cdot cm^{-1}$	1,251	239	3,906	43.2
DO	$mg \cdot dm^{-3}$	8.5	1.7	15.8	30.1
TDS		1033	184	2836	39
Ca^{2+}		105.7	33.12	176.4	20.3
Mg^{2+}		17.0	4.84	32.7	27.6
Na^+		166.3	8.56	827.8	80.0
K^+		10.4	2.89	20.8	26.7
Li^+		0.04	0.00	0.2	57.5
HCO_3^-		533.9	113.23	1,474.6	42.2
SO_4^{2-}		70.1	11.77	168.5	39.2
Cl^-		124.6	9.52	866.9	99.3
F^-		0.2	0.08	0.7	34.5
NH_4^+		0.4	0.00	20.1	279.9
NO_3^-		3.8	0.00	14.1	70.2
NO_2^-		0.1	0.00	0.9	124.2
PO_4^{3-}		0.1	0.00	3.8	453.6
TIN		1.2	0.01	15.6	84.9
TN		2.1	0.44	16.9	63.3
TON		0.9	0.00	7.7	108.3
TIC		97.1	33.99	428.6	54.9
TC		105.8	40.75	475.2	55.0
TOC		9.0	0.00	47.4	88.9

Explanations: *CV* = coefficient of variation, *T* = temperature, *EC* = electrical conductivity, *DO* = concentration of dissolved oxygen, TDS = water mineralisation, *TIN* = total inorganic nitrogen, *TN* = total nitrogen, *TON* = total organic nitrogen, *TIC* = total inorganic carbon, *TC* = total carbon, *TOC* = total organic carbon.
Source: own study.

Among nitrogen compounds, NO_3^- reached the highest concentrations (3.8 mg·dm^{-3}), and the average total nitrogen was *TN* = 2.1 mg·dm^{-3}. Phosphate concentrations in the studied waters were also at very low levels. The average total carbon (*TC*) concentration was 105.8 mg·dm^{-3}, with inorganic carbon (*TIC*) forms clearly dominating (Tab. 1). The exceptionally low concentrations of nitrogen, phosphorus, and organic carbon compounds in the waters of the Drwinka River are particularly surprising. Many studies identify urbanised areas as the primary sources of these substances in river waters (Zan *et al*, 2012; Glińska-Lewczuk *et al.*, 2016; Choi *et al*, 2024). However, in many of the analysed water samples, it was not possible to determine the concentrations of nitrogen and phosphorus compounds because their values were below the detection limit (e.g., in approximately 80% of the samples, PO_4^{3-} concentrations were below the detection limit, as well as NO_2^- concentrations in 30% of the samples).

Analysis of variance (ANOVA) and the Scheffé post-hoc test for p = 0.05 revealed the presence of statistically significant seasonal differences for most physicochemical parameters of water. No significant seasonal differences were observed for the following parameters: *DO* deficit, *EC*, TDS, Mg^{2+}, Na^+, Cl^-, and *TON*. The lack of seasonal variability in Na and Cl ion concentrations results from the continuous year-round inflow of these ions with industrial wastewater into the river. Moreover, anthropogenic pollution is the primary source of these ions in the water of the Drwinka River. For most parameters, it was found that winter concentrations differed significantly from concentrations in other seasons. In the case of *DO*, Ca^{2+}, SO_4^{2-}, and *TIN*, the highest values were observed in winter in the water of the Drwinka River (Fig. 2). Conversely, *T*, pH, *TIC*, and *TOC* reached their lowest values in the river water during winter (Fig. 2). In temperate climates, water temperatures exhibit seasonal patterns similar to air temperatures. During the summer months, water temperatures in streams and rivers increase significantly, reflecting the higher air temperatures (Punzet *et al.*, 2012). In contrast, *DO* exhibits inverse seasonality. The relationship between *DO* in water and *T* is well-documented, showing a clear negative correlation: as *T* rises, the solubility of oxygen decreases, resulting in lower *DO* concentrations (Bogdał *et al.*, 2016). Seasonal variations in biological activity, such as photosynthesis and respiration, play a crucial role in shaping the concentrations of N, P, and C compounds in water. Higher temperatures in summer promote photosynthesis and microbial activity, leading to increased *TOC* concentrations. In winter, reduced sunlight and lower temperatures decrease these activities, resulting in lower carbon concentrations (Berg *et al.*, 2021). Storm events and seasonal floods can also significantly impact carbon levels. During storms, the influx of new water can raise *TOC* concentrations by flushing terrestrial organic material into rivers (Górniak, 2017). This is precisely why the greatest variability in *TC* and *TOC* concentrations in the Drwinka River water is observed during the summer and autumn seasons. Multiple studies indicate that *TIN* concentrations in river water are generally higher in winter. This is attributed to reduced plant uptake during colder months, leading to less nitrogen assimilation and more nitrogen remaining in the water. In contrast, during summer, increased biological activity and plant growth result in higher nitrogen uptake, reducing the *TN* concentrations in river water (Wang *et al.*, 2016). Nevertheless, the studies also identify additional factors, such as agriculture and fertilisation, as well as hydrometeorological conditions, which also play an important role in the seasonal variability of nitrogen compounds (Exner-Kittridge *et al.*, 2016; Matej-Lukowicz *et al.*, 2020).

SPATIAL DIVERSITY OF WATER CHEMISTRY

Figure 3 illustrates the changes in mineralisation and the structure of the chemical composition along the course of the Drwinka River. An increase in water mineralisation is observed, from approximately 550 mg·dm^{-3} to around 1500 mg·dm^{-3}, with noticeable spikes in TDS following the discharge of wastewater

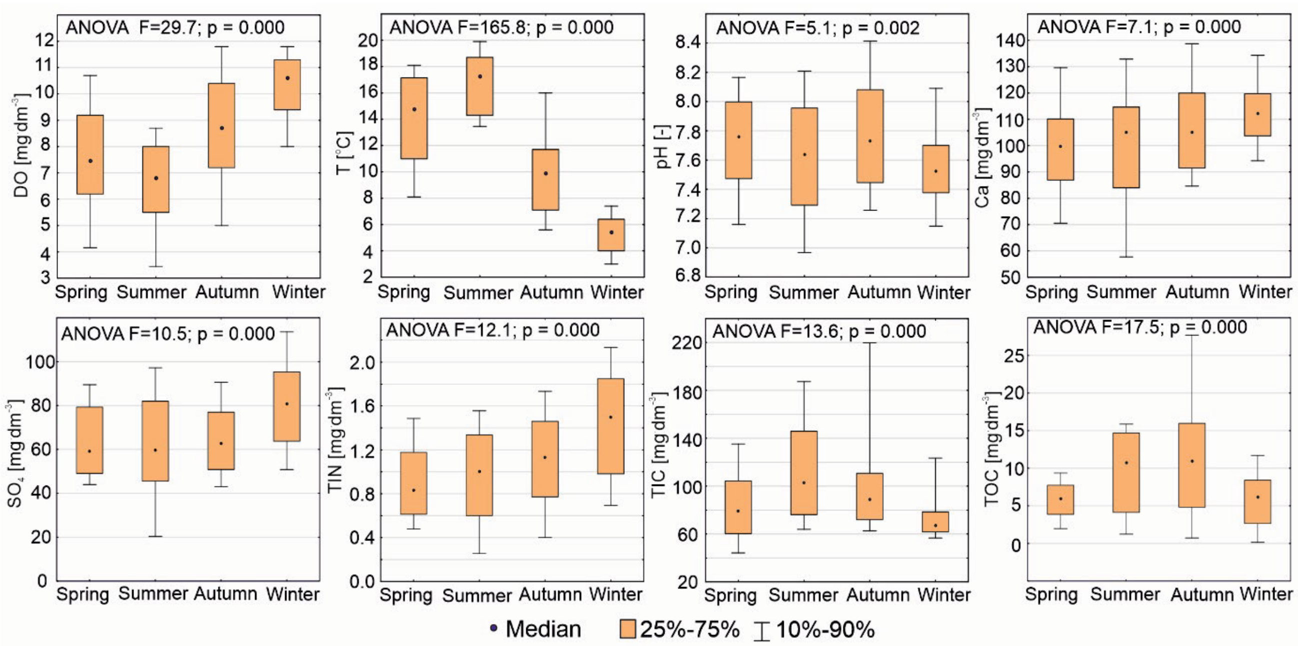

Fig. 2. Seasonal changes in selected physicochemical parameters of the Drwinka River water; *F* = *F*-statistic, *p* = significance level, *DO*, *T*, *TIN*, *TIC*, *TOC* as in Tab. 1; source: own study

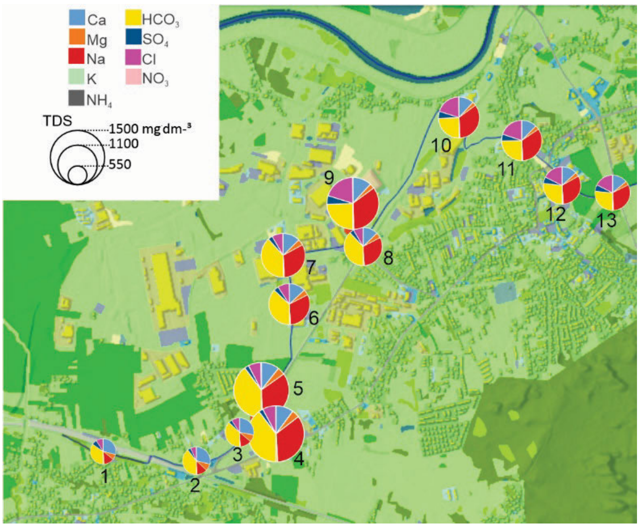

Fig. 3. Changes in the structure of the chemical composition of water along the course of the Drwinka River; TDS = water mineralisation; source: own study

(sites 4 and 9) from industrial facilities located in the economic zone. These wastewater inflows lead to changes in the structure of the chemical composition of Drwinka River waters. In the upper course of the river (sites 1–3), HCO_3^- (~37%) and Ca^{2+} (~31%) were dominant in the water. After the wastewater discharge at site 4, the share of Na^+ in the water structure significantly increased (3 times), from 8 to 25%, while the share of Ca^{2+} nearly halved. Following the second wastewater discharge (site 9), the share of Cl^- in the water doubled. These changes in the chemical composition structure result in a transition of the hydrochemical type of water from a simple HCO_3-Ca type to a more complex HCO_3-Cl-Na-Ca type. The total contribution of nitrogen and phosphorus compounds in the waters does not exceed 0.5%. The increase in surface water salinity, especially due to the input of NaCl, caused by wastewater discharges, surface runoff, or pollution outflows from various industrial sectors in urbanised areas, is a common problem observed worldwide (Halabowski *et al.*, 2020; Kaushal *et al.*, 2021; Singh *et al.*, 2025).

Figure 4 illustrates the changes in the physicochemical parameters of the Drwinka River water along its course through the industrial and residential-service zones. It is evident that the most significant changes, primarily increases in values, occur in the river water directly after the inflow of wastewater from the industrial zone, as these wastewater inflows are characterised by higher values of most physicochemical parameters than the Drwinka River water. Numerous studies indicate that cities and industrial zones significantly influence the chemistry and quality of river water (Schliemann, Grevstad and Brazeau, 2021). Pollution hotspots in these regions are areas where pollutants,

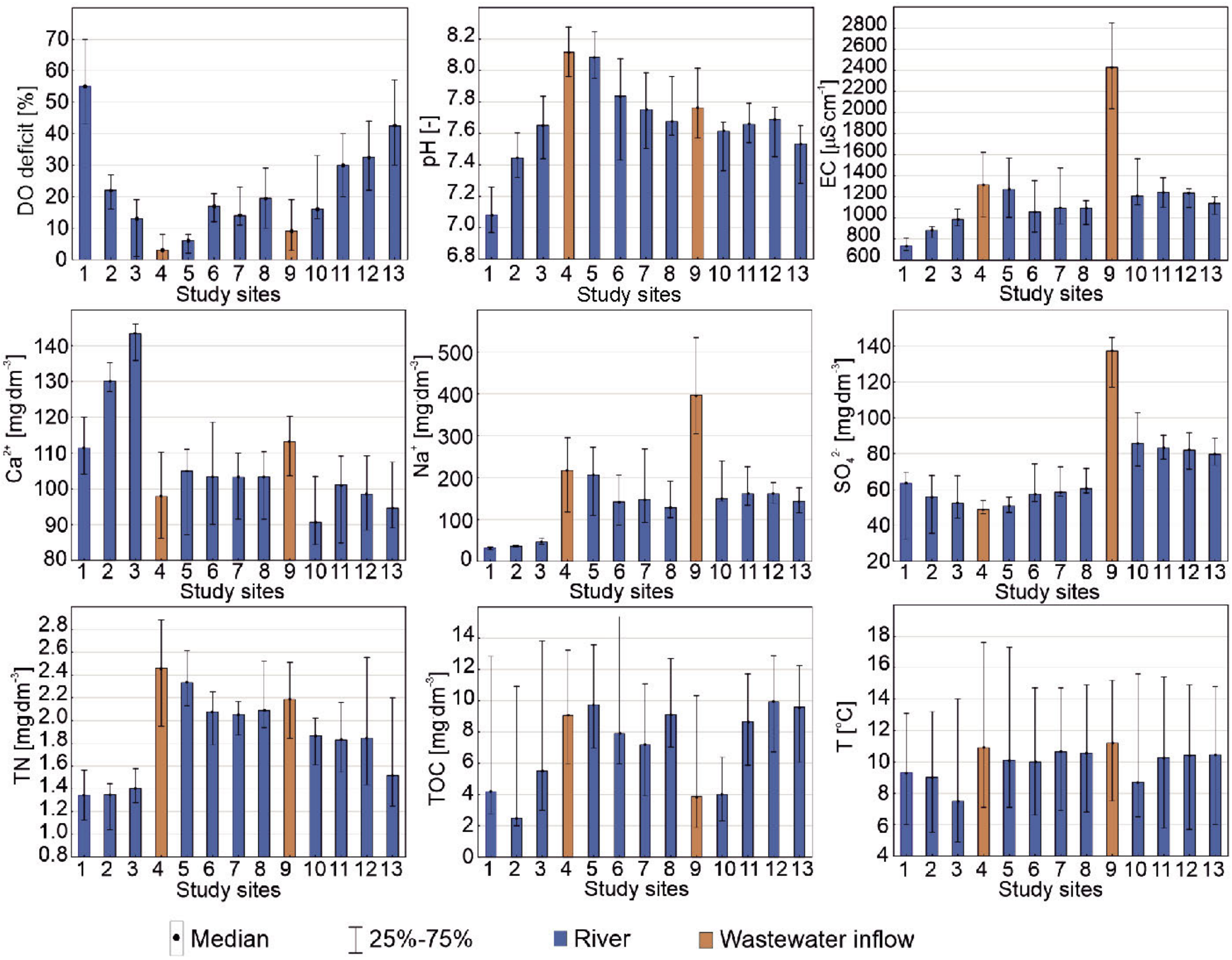

Fig. 4. Changes in the values of selected physicochemical parameters of water along the course of the Drwinka River; *DO*, *EC*, *TN*, *TOC*, *T* as in Tab. 1; source: own study

such as heavy metals, organic compounds, and excess nutrients (including nitrogen compounds), are introduced at high concentrations (Singh *et al.*, 2025). These hotspots often coincide with industrial discharges, urban runoff, and combined sewer overflows, creating localised areas of severe contamination.

Particular attention should be given to the changes in the *DO* deficit. In the river's upper course, the *DO* deficit decreases. However, despite the fact that the incoming wastewater is well-oxygenated (*DO* deficit below 10%), an increase in the *DO* deficit is observed as the river flows through the urban area (Fig. 4).

Additionally, the Niepołomice city raises the river water temperature by approximately 2°C and affects the water's pH (Fig. 4). The increase in river water temperature after passing through the city is due both to the inflow of warmer wastewater and the urban heat island effect. Similar causes of the city's impact on water temperature were identified for the Suceava River by Briciu *et al.* (2020); however, the water temperature increase there was smaller, amounting to 3.7%. In the case of the Drwinka River, the temperature increase is approximately 4.7%.

The wastewater inflows nearly double the concentrations of *TN* compared to the river water. However, after the initial increase in nitrogen concentrations caused by the wastewater inflows, a gradual decrease is observed. By the time the river reaches study site 13, the *TN* concentrations are nearly equivalent to those observed in the river's upper course.

The decrease in nitrogen concentrations in the water is caused by the presence of well-developed hydrophilic vegetation in many sections along the river's course and within its channel (particularly between sites 6–8 and sites 11–13). The most commonly found plants in the river include: *Phragmites australis*, *Glyceria maxima*, *Typhaceae*, *Lemna minor*, and *Ceratophyllum demersum*. These plants have a high capacity to absorb nutrients, particularly nitrogen and phosphorus, from polluted water. They are also effective in accumulating heavy metals such as cadmium, lead, and zinc, making them a valuable species for phytoremediation in contaminated environments. The roots of hydrophyte plants help absorb and stabilise sediments and serve as habitats for microbial communities responsible for processes such as the transformation of N, P, and C compounds (Kalu, Rauwane and Ntushelo, 2021).

Additionally, the increase in water temperature and pH may have contributed to the reduction in *TN* concentrations, particularly NO_3^-. Studies show that higher temperatures increase the nitrate reduction rate (Chen, Yang and Wang, 2016). Simultaneously, raising the water's pH to approximately 7.5–7.8 enhances the denitrification rate. Research indicates that water alkalinisation, as long as it remains below pH 9.0, can improve nitrate removal efficiency by up to 98% (Miao *et al.*, 2024).

FACTORS SHAPING WATER CHEMISTRY

Pearson correlation matrix illustrates the relationships between various physicochemical parameters of Drwinka River water (Tab. 2). The major ions (Na^+, Cl^-, SO_4^{2-}, HCO_3^-) cluster together and show a positive correlation with *EC* and TDS, reflecting their shared contribution to the river's mineralisation.

Table 2. Pearson's correlation matrix of selected physicochemical parameters in Drwinka River water

	DO	***T***	**Ca**	**K**	**NO_3**	***TOC***	**pH**	***EC***	**TDS**	**Mg**	**Na**	**HCO_3**	**SO_4**	**Cl**	**PO_4**	***TIN***	***TN***	***TON***	***TIC***
T	**-0.49**																		
Ca	**0.24**	**-0.29**																	
K	-0.08	**0.24**	0.01																
NO_3	**0.43**	**-0.11**	**-0.16**	0.30															
TOC	-0.05	-0.02	-0.07	0.17	-0.02														
pH	**0.30**	**0.14**	**0.15**	0.44	**0.41**	**0.24**													
EC	0.07	**0.33**	0.05	0.38	**0.33**	-0.10	**0.47**												
TDS	0.08	**0.36**	**0.14**	0.50	**0.38**	-0.09	**0.59**	**0.95**											
Mg	**0.22**	0.07	**0.70**	0.42	**0.15**	0.02	**0.46**	**0.23**	**0.44**										
Na	0.03	**0.35**	**-0.26**	0.38	**0.48**	-0.01	**0.53**	**0.89**	**0.87**	0.04									
HCO_3	0.06	**0.40**	**0.22**	0.58	**0.35**	-0.04	**0.60**	**0.63**	**0.82**	**0.74**	**0.58**								
SO_4	**0.15**	**-0.25**	**0.17**	0.00	**0.25**	**-0,14**	0.06	**0.53**	**0.42**	0.11	**0.45**	-0.02							
Cl	0.06	**0.14**	-0.08	0.13	**0.27**	0.10	**0.29**	**0.85**	**0.72**	**-0.14**	**0.83**	**0.22**	**0.67**						
PO_4	-0.08	**0.28**	-0.16	0.22	-0.05	0.04	**0.20**	**0.20**	**0.22**	0.03	**0.24**	**0.23**	-0.05	**0.11**					
TIN	**0.29**	**-0.29**	**0.19**	0.20	**0.43**	-0.01	**0.12**	**0.24**	**0.24**	**0.16**	**0.18**	**0.15**	**0.31**	**0.22**	-0.05				
TN	**0.25**	-0.08	**-0.18**	**0.22**	**0.51**	**0.46**	**0.27**	**0.24**	**0.23**	-0.06	**0.35**	**0.13**	**0.14**	**0.25**	0.09	**0.51**			
TON	0.01	-0.01	**-0.29**	**-0.17**	**0.11**	**0.17**	0.00	0.07	0.00	**-0.30**	**0.21**	**-0.12**	**0.13**	**0.19**	0.05	**-0.27**	**0.29**		
TIC	0.05	**0.32**	0.06	**0.46**	**0.27**	**0.49**	**0.57**	**0.39**	**0.53**	**0.49**	**0.43**	**0.68**	**-0,16**	0.09	0.11	0.08	**0.49**	0.07	
TC	0.04	**0.30**	0.03	**0.46**	**0.25**	**0.60**	**0.58**	**0.35**	**0.49**	**0.45**	**0.41**	**0.64**	**-0.18**	0.07	**0.13**	0.07	**0.52**	0.08	**0.99**

Explanations: statistically significant correlation coefficients (p = 0.05) are highlighted in bold; *T*, *TOC*, *EC*, TDS, *TIN*, *TN*, *TON*, *TIC*, *TC* as in Tab. 1.
Source: own study.

This also indicates that they are influenced by similar processes, such as the input of pollutants from the industrial zone. A similar impact of urban areas (in Zakopane), resulting in a sudden increase in the concentrations of Na^+ and Cl^- ions in the Biały Dunajec River, was demonstrated by Lenart-Boroń *et al.* (2017). Organic carbon, nitrogen, and phosphorus compounds show weak or no correlation with other physicochemical parameters. Therefore, their concentrations in the water may additionally be shaped by other natural or anthropogenic factors occurring within the catchment area. This occurs due to the complex interactions between biological, chemical, and physical processes that influence nutrient cycling in rivers (Xia *et al.*, 2018).

Principal Component Analysis (PCA) identified four factors shaping the physicochemical parameters of the water. These factors explain the variability as follows: factor 1 – 30%, factor 2 – 15.6%, factor 3 – 13.8%, and factor 4 – 11.5% (Fig. 5B, C). Factor 1 is associated with *EC*, pH, most major ions (except Ca^{2+} and SO_4^{2-}), *TC*, *TIC*, and *TN*. It reflects the spatial variability in water chemistry along the course of the Drwinka River and highlights changes influenced by urbanisation. Figure 5A shows three distinct groups of points: those located in the upper course of the river before the industrial zone, points within the industrial and urban zone, and the wastewater inflow (site 9). Factor 2 highlights the chemistry of wastewater, as evidenced by high factor loadings for *EC*, Na^+, Cl^-, and SO_4^{2-}. Factor 3 reveals a relationship between parameters such as *DO*, *T*, Ca^{2+}, Mg^{2+}, *TIN*, and *TON*, which may indicate natural seasonal changes related to vegetation. Meanwhile, factor 4 is associated with *T*, *TOC*, and *TN*.

Thus, the first two factors shaping water chemistry are related to anthropogenic pressure, manifested through land use changes and point sources of pollution. Similar results were obtained by Yang *et al.* (2022), who found that the main sources of water quality deterioration were land use changes and industry (accounting for 42.1% of the variability). However, the contribution of these sources to shaping water quality varied depending on hydro-meteorological conditions (drought-rainfall). The increase in dissolved salts, especially Na^+ and Cl^-, in urban rivers is associated with the delivery of pollutants from various sources, such as effluent discharges from wastewater treatment plants, stormwater drainage, industrial pollution, and a higher proportion of impervious surfaces. Freshwater salinisation can mobilise base cations (Ca^{2+}, Mg^{2+}, K^+) and metals (for example: Cu, Cd, Zn) to streams through accelerated ion exchange, stimulate different biogeochemical processes by altering pH and ionic strength, and exacerbate eutrophication (Duan and Kaushal, 2015; Haq, Kaushal and Duan, 2018). In contrast, the third and fourth factors are driven by natural processes resulting from seasonal changes occurring in a temperate climate and the seasonal variability of vegetation growth. The seasonality of vegetation in a temperate climate influences the processes shaping the chemistry of river water. During the period of intense plant growth (spring and summer), plants absorb significant amounts of nutrients, such as nitrogen (N) and phosphorus (P), which may be present in the water. As a result of this process, the concentration of these nutrients in the water is reduced, which can lead to a decrease in the risk of eutrophication (Puczko and Jekatierynczuk-Rudczyk, 2020). After the growing season ends (in autumn and winter) and leaves fall, various nutrients and organic matter from plants may enter the water, which can lead to an increase in nutrient concentrations. This phenomenon is particularly evident during the period when plants begin to die and decompose. Wider and well-maintained riparian zones are crucial for mitigating urban impacts on water quality, particularly in regions with high impervious surface cover (Singh *et al.*, 2021). Riparian vegetation directly affects water quality through several mechanisms: filtration of runoff, temperature regulation, nutrient uptake and cycling, faecal contaminant trapping (Kumwimba *et al.*, 2024). Vegetation provides shade, reducing solar heating of

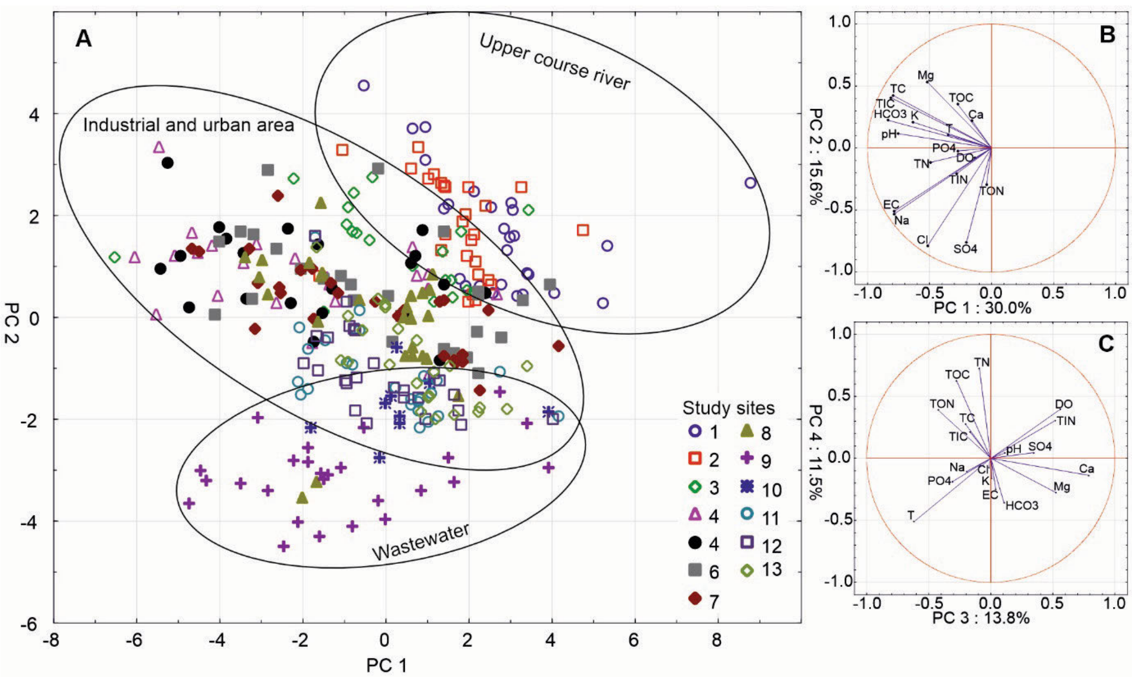

Fig. 5. Principal Component Analysis of water chemistry: scatter plots for the coordinates of cases for PC1 and PC2, including study sites (A), and the projection of factor loadings for PC 1×2 (B) and PC 3×4 (C); *T*, *TOC*, *EC*, TDS, *TIN*, *TN*, *TON*, *TIC*, *TC*, *DO* as in Tab. 1; source: own study

river water. This is way riparian zones enhance thermal regulation, which is essential for maintaining dissolved oxygen levels and aquatic ecosystem health (Zhang *et al.*, 2021).

CONCLUSIONS

Urban areas with industrial zones pose a significant threat to the water quality of nearby rivers. Studies have shown that the high concentration of industrial facilities within a confined area leads to the introduction of various pollutants into the water. It has been found that the most pressing issue in industrial zones is the sudden increase in water salinity (Na^+ and Cl^- ions), caused by point sources of pollution discharging into the rivers. Urban areas contribute to a decrease in dissolved oxygen, water pH, and are a source of biogenic compound inputs. Point sources of pollution represent "hotspots" of water quality deterioration within the city.

The results showed that anthropogenic pressure, related to land use changes and the discharge of sewage, shapes the water chemistry of the Drwinka River by almost 50%. Meanwhile, 25% of the impact is attributed to natural processes related to vegetation interaction and seasonal climate variability.

The presence of hydrophytic vegetation along riverbanks and within the riverbed helps mitigate this issue. The introduced pollutants, primarily organic and inorganic biogenic compounds such as nitrogen, phosphorus, and carbon, undergo transformation and are taken up by plants, leading to a gradual decrease in their concentrations along the river course. Studies have shown that during the growing season, total nitrogen concentrations are significantly lower than in the winter period, which confirms the important role of riparian vegetation. Therefore, preserving and/or introducing hydrophytic vegetation into the riparian zone is essential for improving water quality and mitigating the negative impacts of industrial areas.

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CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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