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ORIGINAL PAPER

Optical properties of dissolved organic matter (DOM) in trophically diverse streams in the Świdwie Nature Reserve*

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Abstract

Dissolved organic matter (DOM) plays a key role in carbon cycling and water quality in shallow, eutrophic freshwater systems. This study examined the spatial variability of DOM in trophically diverse streams in the Świdwie Nature Reserve (NW Poland) during early autumn circulation. Physicochemical analyses were combined with UV-Vis spectroscopy, fluorescence excitation-emission matrices (EEMs) and PARAFAC modelling to characterize DOM sources and transformation pathways. Dissolved organic carbon (DOC) concentrations (12.7-37.4 mg L^{-1}) revealed strong contrasts between tributaries. Water bodies rich in fresh organic matter (the Gunica River) contained low-aromatic DOM, whereas water bodies rich in highly humified DOM (Struga Żurawia and the Bolków-Łęgi Canal) contained aromatic, terrestrially derived DOM enriched in nutrients. Optical indices ($SUVA_{254}$, a_{280}, a_{350}, E_{250}/E_{365}, SR) and fluorescence parameters (BIX, HIX, f_4/f_5) consistently distinguished autochthonous from allochthonous DOM. PARAFAC identified two humic-like components: C1, associated with less humified, microbially derived DOM, and C2, representing more aromatic, fulvic-like material. Multivariate analyses (CCA, clustering, Pearson correlations) indicated that nutrient enrichment, conductivity and humification degree were the main drivers of DOM variability. The strong positive relationship between total fluorescence and conductivity suggests that ionic enrichment enhances DOM optical activity. These findings highlight the sensitivity of small, shallow catchments to natural and anthropogenic pressures and demonstrate the effectiveness of optical methods in resolving DOM dynamics.

Keywords: DOM, streams, fluorescence, UV-Vis, PARAFAC, soluble biogenic compounds

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INTRODUCTION

Inland waters are heterogeneous ecosystems whose functioning depends on the continuous input and transformation of dissolved organic matter (DOM) from autochthonous and allochthonous sources. Autochthonous DOM is produced within the system by periphyton, macrophytes, phytoplankton and microbes, whereas allochthonous material is supplied from soils, wetlands and terrestrial vegetation. This often dominates in small wetland catchments (Allan, Castillo 2007, Tank et al. 2010). DOM ranges from labile, low-molecular-weight compounds to highly aromatic, humified macromolecules, undergoing microbial and photochemical degradation, sedimentation, and incorporation into food webs. Due to its strong UV-Vis absorption properties, DOM can regulate light penetration, thermal structure and primary production (Kowalczuk et al. 2010, Prokowski, Mielnik 2012, Arvola et al. 2025). UV-Vis absorbance and fluorescence EEMs are optical tools that can effectively characterize the sources, aromaticity and humification of DOM (Murphy et al. 2013, Fasching et al. 2016, Coch et al. 2019, Carstea et al. 2020, Ma et al. 2023). Numerous studies have highlighted the diagnostic value of these tools in distinguishing between terrestrial and autochthonous DOM, as well as in tracking degradation processes (Cory, Kaplan 2012, Gonçalves-Araújo et al. 2015).

Small, shallow, productive catchments respond strongly to hydrological fluctuations and seasonal changes, particularly after the growing season when the quantity and composition of DOM is altered by mixing, rainfall and the decay of primary producers (Toming et al. 2013, Shao et al. 2024). In wetland-dominated systems such as Lake Świdwie, interactions among organic soils, agricultural drainage, and internal lake processes lead to distinct differences between autochthonous and allochthonous DOM (Lambert et al. 2017, Pisani et al. 2020).

Despite the ecological importance of the Świdwie Nature Reserve, the variability of DOM among its tributaries during autumn circulation remains poorly understood. We hypothesized that post-vegetation conditions would increase CDOM and FDOM concentrations due to intensified degradation and increased allochthonous inputs. We predicted that wetland and agricultural streams would supply more aromatic, humified DOM and that the main river inflow would transport fresher, less aromatic, autochthonous material.

This study aims to characterize the spatial variability of DOM optical properties across the Lake Świdwie catchment, identify the dominant sources of DOM and its transformation pathways, and determine the environmental factors that shape its composition during the post-vegetation period. Physicochemical measurements were combined with UV-Vis spectroscopy, fluorescence EEMs and PARAFAC modelling to provide new insights into DOM dynamics in small wetland catchments outside the main growing season.

MATERIALS AND METHODS

Study site

Lake Świdwie (53°33’30″ N, 14°22’20″ E) is a small, shallow lake (61.41 ha; 0.7 m deep) surrounded by extensive wetlands. Located within the Świdwie Nature Reserve, which was established in 1963, the lake has been protected under the Ramsar Convention since 1984 and designated as a Natura 2000 site (PLB320006) since 2004. The area is an important habitat for 150-200 species of birds (Jasiński, Staszewski 2013, Environmental Protection Programme for the West Pomeranian Province 2030, 2021).

The lake is highly eutrophic and polymictic, making it highly susceptible to degradation (Category III; Gałczyńska 2013). Overgrowth has been accelerated by agricultural pressures and inadequate wastewater management. Recommendations for protecting the lake included limiting afforestation and directing wastewater to municipal systems or sealed tanks to avoid infiltration due to high groundwater levels. Current threats include altered hydrology, degradation of meadows and reed beds, disappearance of small water bodies, overgrowth of the lake, and a decline in biodiversity. External pressures include increased tourist traffic, human presence, and poaching.

Sample collection

Water samples were collected from rivers within the Lake Świdwie catchment in October, during the early autumn circulation period. Samples were taken from the surface layer (0.2 m). Sampling locations are shown in Figure 1.

Physicochemical analyses

The following parameters were measured: the concentration of ammonium nitrogen, nitrite nitrogen, nitrate nitrogen, mineral nitrogen (Nmin = $N–NO_3^-$+$N–NO_2^-$ $N–NH_4^+$), phosphates, dissolved oxygen, pH and electrical conductivity. The concentration of dissolved oxygen in the water samples was measured using a microprocessor-based dissolved oxygen meter (model HI9145) from Hanna Instruments. The pH of the water was measured using a potentiometric pH-meter (model CI-316). Conductivity was determined using an N5721M conductometer. Chemical analyses followed Standard Methods (PN 76/C 04576.01, PN 73/C 04576.06, PN 82/C 04576.08, PN EN 1189:2000). Analytical quality was ensured through standardization, blanks, spiked samples and duplicates.

DOC determination and sample preparation

To determine the DOC and conduct the optical analyses, the water samples were filtered twice through membrane filters to remove suspended particles and phytoplankton cells. DOC was measured using a spectrophotometer after wet oxidation with $K_2Cr_2O_7$ and heating at 140°C for 20 min,

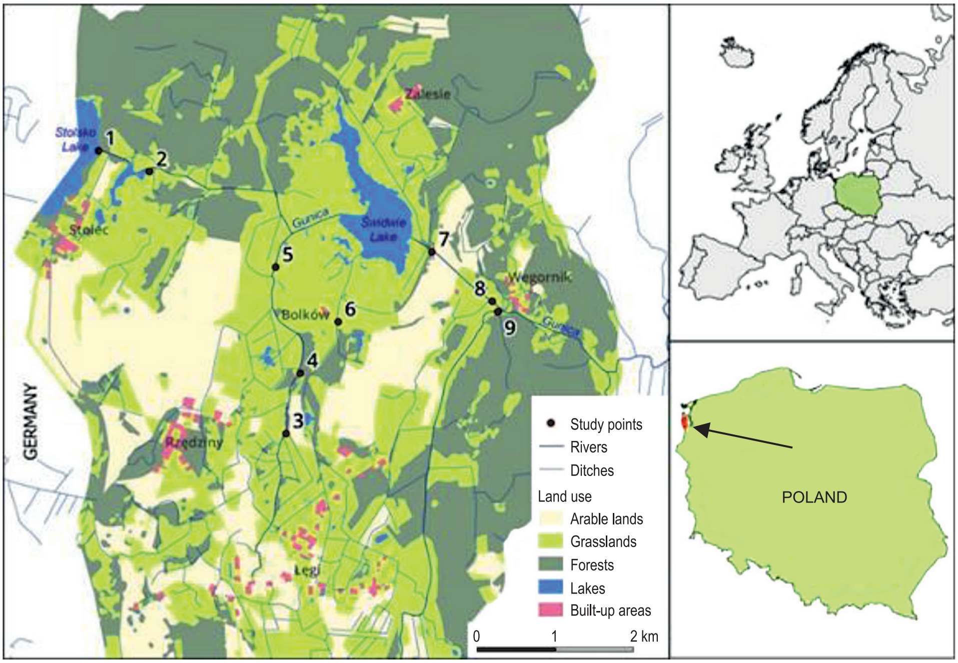

Fig. 1. Location of water samples: sites 1 and 2 – the Gunica River (inflow) – originates from Lake Stolsko; characterized by low nutrient concentrations, sites 3, 4 and 5 – the Struga Żurawia (inflow) – drains agricultural areas and meadows with low cattle density (site 3 – near a wastewater pumping station, site 4 – before entering the Żurawie wetland basin – a habitat for cranes, site 5 – after leaving the basin), site 6 – the Bolków-Łęgi Canal (inflow) – strongly influenced by agricultural runoff and meadow drainage, sites 7 and 8 – the Gunica River (outflow) – site 7 – direct outflow from the lake, site 8 – near a newly established agritourism farm, site 9 – the Mała Gunica River – drains nearby municipalities; waters often enriched in phosphorus

after which the samples were evaporated to constant mass.

UV-Vis absorbance measurements

Absorbance spectra were recorded using a Specord M42 UV-Vis spectrophotometer (Zeiss Jena) in the range 220-700 nm with a 1 cm quartz cuvette. The following optical indices were calculated: specific absorption coefficient: $a^*_\lambda = 2{,}303\ A_\lambda\ L^{-1}$ (where : a^*_λ is absorbance at wavelength λ and L is the optical path length (m)), $SUVA_{254}$ (absorbance at 254 nm normalized to DOC) – Westerhoff, Anning (2000), spectral slope ratio ($SR = S_{275\text{-}295/S350\text{-}400}$) – Helms et al. (2008) and E_{250}:E_{365} ratio.

Fluorescence spectroscopy

Fluorescence excitation-emission matrices (EEMs) were recorded using a Hitachi F 7000 spectrofluorometer equipped with a xenon lamp and a 1 cm quartz cuvette. Emission spectra (Em) were scanned over a wavelength range of 250-600 nm by varying the excitation wavelength (Ex) between 200 and 500 nm. Spectra were recorded at a scanning speed of 240 nm min^{-1}, with slit widths of 5 and 10 nm for excitation and emission, respectively. The scanning interval for excitation and emission was 10 nm. The EEMs were corrected and calibrated in accordance with the methodology described by Murphy et al. (2013). PARAFAC modelling was performed using the N-Way Toolbox in MATLAB 15 to identify statistically independent fluorescent components. All spectra were recorded at 25°C.

Statistical analysis

The statistical analyses were conducted using R (R Core Team, 2021) and PAST 4.07 (Hammer et al. 2001). Canonical Correspondence Analysis (CCA) was employed to investigate the relationships between environmental variables and fluorescence components (component 1, component 2 and IFtot). A two-way dendrogram approach was used to assess similarity among sampling sites and variables using hierarchical clustering (Ward's method, Euclidean distance). The Pearson correlation coefficients were calculated in accordance with the recommendation that the Pearson's method can be used even when the data deviate from normality (McDonald 2014).

RESULTS AND DISCUSSION

Physicochemical properties of water samples

The presence of nitrogen, phosphorus and carbon has a significant impact on trophic status and the mineralization of organic matter. DOC is a key indicator of DOM processing (Hansen et al. 2016) and typically ranges from 2 to 25 mg L^{-1} (Miller, McKnight 2010). However, in the catchment under study, DOC concentrations were much higher (12.7-37.4 mg L^{-1}; see Table 1), exceeding typical river values of less than 10 mg L^{-1}. Hydrology, particularly precipitation and runoff, is known to enhance DOM transport (Ji et al. 2021), which explains the increase in DOM concentration and humification in autumn.

The highest DOC concentrations were observed at sites 3, 5 and site 6 (34-37.4 mg L^{-1}), reflecting the presence of wetland soils, agricultural drainage, and organic enrichment. The lowest DOC value (12.7 mg L^{-1}) at site 9 resulted from phosphorus-rich but carbon-poor municipal runoff. Intermediate values characterized sites 1, 2, 4 and 8. DOC at the lake outflow (>30 mg L^{-1}) indicates enhanced export during autumn mixing, which is consistent with increased release through resuspension and phytoplankton decay (Begum et al. 2025).

Dissolved oxygen, phosphate and conductivity patterns also indicated degraded water quality. Oxygen deficits were likely caused by high loads

Table 1

Average values of water quality parameters in individual locations of the Lake Świdwie catchment area

Sampling site		pH	DOC (mg L^{-1})	N_{min} (mg L^{-1})	DOC:N_{min}	O_2 (mg L^{-1})	P-PO_4 (mg L^{-1})	EC (μS cm^{-1})
Gunica River (inflow)	1	7.76	19.39	0.846	22.92	5.18	0.057	287
	2	7.79	22.61	0.980	22.45	5.46	0.017	366
Struga Żurawia (inflow)	3	7.55	35.07	0.244	143.7	4.19	0.358	550
	4	7.00	21.43	0.632	33.91	2.16	0.144	547
	5	7.40	34.05	3.456	9.85	0.93	0.431	661
Bolków-Łęgi Canal (inflow)	6	7.21	37.38	4.574	8.17	0.44	0.509	481
Gunica River (outflow)	7	7.31	33.25	0.578	57.52	3.80	0.168	462
	8	7.61	19.81	0.631	31.40	4.08	0.167	475
Mała Gunica River (outflow)	9	7.40	12.71	0.873	14.56	4.95	0.269	519

of labile organic matter from avifauna (Sø et al. 2022). The elevated phosphate levels at sites 3, 5 and 6 suggest internal loading from enriched sediments (Welch et al. 2005), which may persist after summer (Lu et al. 2021). Mineral nitrogen levels were generally low, except at sites 1, 2 and 9, where 5-6-fold increases indicated recent agricultural inputs, comparable to short-term pulses in small catchments (Van Meter et al. 2018). Conductivity patterns supported these interpretations: low values at sites 1 and 9 indicated precipitation-dominated inflow, while higher values elsewhere reflected groundwater and anthropogenic influences (Kaushal et al. 2018).

Analysis of UV-Vis spectra

The absorbance coefficients for all sites are shown in Table 2. The low $SUVA_{254}$ values observed at sites 1, 2 and 7 (mean 1.76 L mgC^{-1} m^{-1}) suggest

Table 2

Absorbance coefficients

Sampling site		$SUVA_{254}$	a_{280}*	a_{350}*	E_{250}:E_{365}	$SR_{(275-295/350-400)}$
Gunica River (inflow)	1	1.70	2.63	0.49	10.21	4.29
	2	1.93	3.07	0.74	7.28	3.73
Struga Żurawia (inflow)	3	2.84	4.69	1.25	6.67	2.68
	4	2.96	4.91	1.31	6.67	2.72
	5	3.01	4.97	1.33	6.62	2.72
Bolków-Łęgi Canal (inflow)	6	3.26	5.52	1.71	5.38	2.49
Gunica River (outflow)	7	1.65	2.62	0.60	7.97	3.37
	8	3.07	5.06	1.39	3.38	2.57
Mała Gunica River (outflow)	9	2.59	4.34	1.27	5.97	2.45

the presence of freshly produced, low-aromatic, low-molecular-weight autochthonous DOM (Hansen et al. 2016, Catalán et al. 2021). Higher values at sites 3 and 4 (mean 2.94 L mgC^{-1} m^{-1}) reflect more aromatic, humified DOM originating from wetland soils, whereas similarly elevated values at sites 5, 6, and 8 (mean 3.03 L mgC^{-1} m^{-1}) are characteristic of peat-dominated catchments (Hansen et al. 2016).

The patterns for a_{280} and a_{350} were comparable, with the lowest values observed at sites 1, 2 and 7 and the highest at sites 6 and 8, indicating a stronger terrestrial influence. The a_{280} coefficient correlated strongly with DOC (r=0.89*), confirming its suitability for DOC estimation (Helms et al. 2008, Fredriksson et al. 2025). $SUVA_{254}$, a_{280} and a_{350} were negatively correlated with dissolved oxygen, reflecting the microbial oxygen demand during the degradation of aromatic DOM (Okafor et al. 2021), and positively correlated with conductivity and orthophosphate ($P\text{-}PO_4$), indicating nutrient-rich waters with more terrestrial DOM (Kaushal et al. 2018).

The E_{250}:E_{365} ratio indicates DOM condensation (Mielnik, Kowalczuk 2018). It was the highest at sites 1, 2 and 7, and lowest at sites 6, 8 and 9, which are both affected by agricultural pollution. It correlated negatively with conductivity and $P\text{-}PO_4$, and positively with dissolved oxygen. The $SR_{(275–295/350–400)}$ index exhibited similar spatial patterns, with most samples exhibiting comparable values (mean 2.61). Higher values at sites 1, 2, and 7 (mean 3.80) indicate the presence of lower-molecular-weight DOM in the Gunica River (Helms et al. 2008, Hansen et al. 2016, Zhang et al. 2016).

Fluorescence excitation – emission matrices

Figure 2 shows 3D fluorescence spectra, which enables identification of peak positions, intensities and spectral shifts. Representative EEMs show two dominant humic-like peaks: Peak A (Ex/Em: 225-300/385-470 nm) and Peak B (300-375/370-470 nm), which are characteristic of aromatic, terrestrially derived humic structures (Coble 1996, Gonçalves-Araújo et al. 2015). Longer wavelength emission reflects more aromatic, conjugated structures, whereas shorter wavelengths indicate less aromatic DOM (Murphy et al. 2013). Humic-like fluorescence originates from lignin derivatives, tannins, and polyphenols and it is sensitive to environmental gradients (Fellman et al. 2010).

The fluorescence intensities of peaks A and B were lowest at sites 1, 2 and 7 and highest at sites 3, 5 and 6, indicating stronger terrestrial, humic-rich inputs. Site 9 (Mała Gunica) showed a relatively stronger peak A, suggesting a different humic composition. Two low-intensity protein-like peaks were also detected: peak C (tyrosine-like, Ex/Em 205-240/300-360 nm) and peak D (tryptophan-like, 260-300/280-355 nm). These were most pronounced in the Gunica River samples and indicated fresher, microbially derived dissolved organic matter – DOM (Santín et al. 2009, Mielnik, Kowalczuk 2018). Diagnostic fluorescence indices (Table 3) supported these patterns.

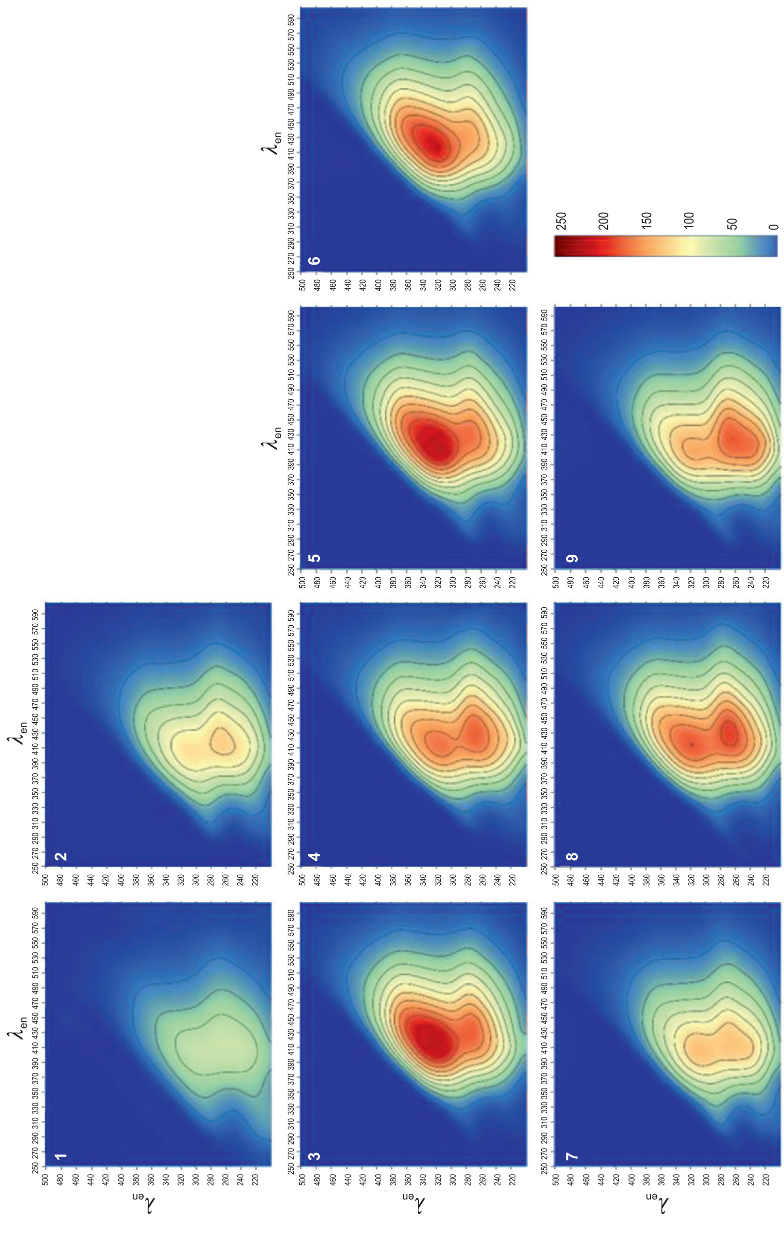

Fig. 2. Classic 3D fluorescence spectra

Table 3

Fluorescence indices

Sampling site		HIX	BIX	f_4/f_5	C1 QSE	C2 QSE	IFl_{to} QSE
Gunica River (inflow)	1	4.20	0.93	1.76	80.4	23.0	103.3
	2	4.54	0.87	1.74	116.4	51.1	167.5
Struga Żurawia (inflow)	3	6.44	0.66	1.71	124.0	161.4	285.4
	4	5.49	0.75	1.72	134.6	116.6	251.1
	5	6.26	0.68	1.71	127.1	153.4	280.5
Bolków-Łęgi Canal (inflow)	6	7.00	0.62	1.74	99.9	156.6	256.5
Gunica River (outflow)	7	4.55	0.87	1.71	125.3	55.3	180.6
	8	5.64	0.73	1.71	137.5	128.6	266.2
Mała Gunica River (outflow)	9	4.88	0.82	1.72	147.4	88.1	235.4

The mean f_4/f_5 value across all sites was 1.72, indicating the predominance of autochthonous DOM with a moderate terrestrial input (Fellman et al. 2010). Higher BIX values at sites 1, 2, 7 and 9 (the Gunica and Mała Gunica rivers) indicate increased microbial activity and the production of fresh DOM. Both indices (BIX and f_4/f_5) confirm their shared sensitivity to autochthonous DOM inputs (Kellerman et al. 2018, Weigand et al. 2022, Ma et al. 2023). In contrast, the humification index (HIX) values were lowest at sites 1, 2, 7 and 9 (the Gunica and Mała Gunica rivers), indicating lower aromaticity and a lower molecular weight of the DOM at these sites. Conversely, higher HIX values at sites 3, 4, 5 and 6 (Struga, Żurawia and Bolków-Łęgi Canal) reflect more humified and terrestrially influenced DOM.

The combination of high BIX and f_4/f_5 values, low HIX values and higher E_{250}/E_{365} and $SR_{(275–295/350–400)}$ values indicates that the DOM in the Gunica River is predominantly autochthonous and weakly humified.

To further characterize the DOM fluorophores, PARAFAC modelling was applied to the corrected EEM dataset (Figure 3). This model served as a complementary tool, enabling the fluorescence signal to be decomposed into inde-

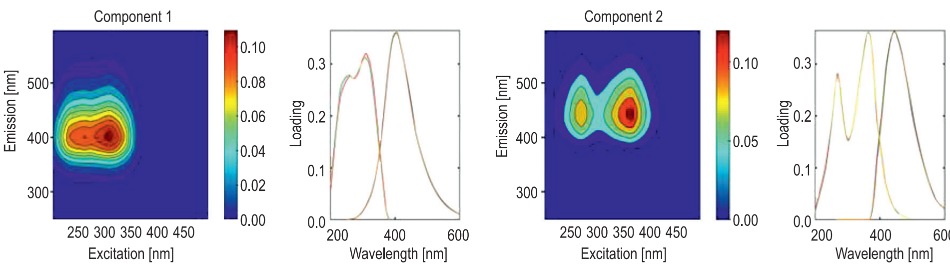

Fig. 3. Contour spectra of EEM components identified by the PARAFAC model and integrated excitation and emission spectra of individual components

pendent components and their respective contributions to be quantitatively compared across sites.

Two humic-like components were identified: C1 (excitation/emission: 220-340/350-450 nm) and C2 (250-400/400-500 nm). C1 is generally found in less humified, microbially influenced DOM, while C2 represents more aromatic, fulvic-like material of terrestrial or mixed origin (Cory, Kaplan 2012, Fasching et al. 2016, Zhao et al. 2017). This interpretation is consistent with previous findings indicating that humic-like fluorophores predominate in waters affected by soil inputs, whereas protein-like components reflect active autochthonous production (Gonçalves-Araújo et al. 2019).

C1 dominated in the Gunica and Mała Gunica rivers (sites 1, 2, 7 and 9), which is consistent with the presence of fresher, less aromatic dissolved organic matter (DOM). In contrast, C2 prevailed at sites 3, 5 and 6 (Struga, Żurawie and the Bolków-Łęgi Canal), indicating a stronger terrestrial influence and higher aromaticity. These patterns were supported by strong correlations: C2 was positively related to HIX (r=0.96) and negatively to BIX (r=−0.99) and f_4/f_5 (r=−0.96), confirming its association with more humified, higher-molecular-weight DOM.

Multivariate analysis

Multivariate analyses revealed a clear ecological separation of DOM characteristics across the catchment. CCA identified two main gradients (Figure 4): one associated with aromatic, humic-rich, high-molecular-weight DOM ($SUVA_{254}$, a_{280}, a_{350}, PO_4, EC) and one representing fresher, less aromatic, low-molecular-weight DOM (E_{250}/E_{365}, SR, f_4/f_5, pH). The strong negative correlation between these two gradients reflects a shift from microbially derived autochthonous DOM to terrestrially influenced, humified DOM along the catchment.

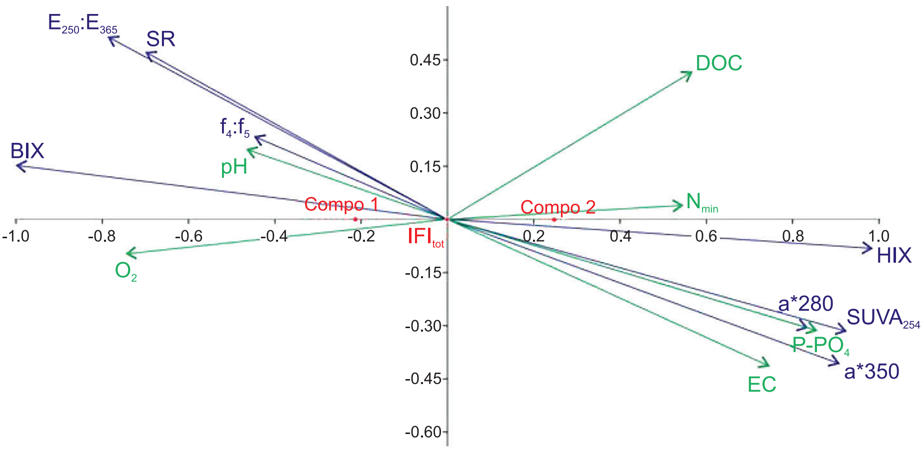

Fig. 4. Two-dimensional projection of DOM and parameters of water quality (environmental variables) on the CCA1 (69.0 %) and CCA2 (13.6 %) axes

As expected, dissolved oxygen was negatively correlated with mineral nitrogen, indicating an increased microbial oxygen demand under nutrient--rich conditions. Predictably, BIX and HIX were negatively correlated, confirming the trade-off between freshly produced and humified dissolved organic matter (DOM).

Component 1 showed a weak positive correlation with BIX, suggesting an association with fresh, microbially derived DOM. Component 2 showed a positive correlation with HIX and a negative correlation with BIX and f_4/f_5, which supports the interpretation that it is an aromatic, humic-like component. IF_{tot} occupied a central position in the ordination, indicating that total fluorescence integrates multiple DOM sources rather than reflecting a single driver.

The elevated SUVA and UV absorbance, as well as the dominance of humic-like components, align with the observations of Gonçalves-Araújo et al. (2015), who associated these patterns with allochthonous, soil-derived DOM and advanced degradation.

Hierarchical clustering (Figure 5) corroborated these patterns, revealing three clusters. Sites 1, 2 and 7 (Gunica River) formed a group characterized

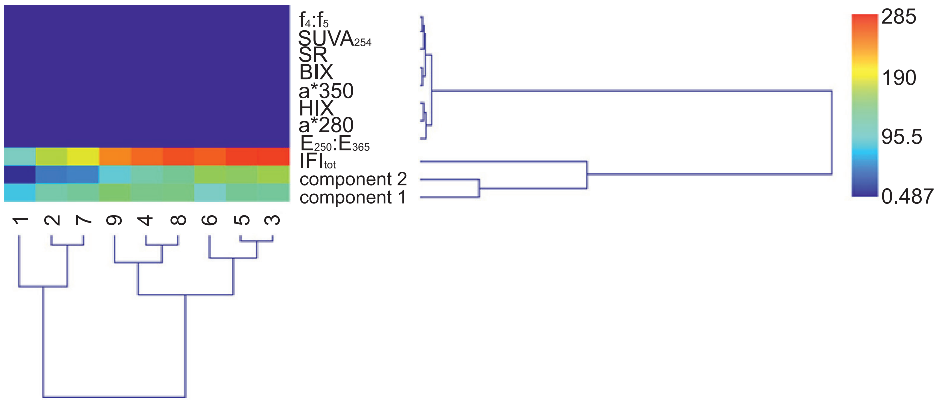

Fig. 5. Hierarchical Cluster Analysis (HCA) was performed using the Euclidean distance and the Ward's method

by low aromaticity, high freshness indices, and the dominance of component 1 (C1). The second cluster (sites 4, 8 and 9) represented a mixture of DOM sources, while sites 3, 5 and 6 formed a third cluster characterized by strongly humified, terrestrially influenced DOM with elevated nutrients, consistent with their catchment settings. The clear separation among the clusters indicates that the analysed variables effectively differentiate the sites.

As shown in Figure 6, the Pearson correlations identified component 2 (C2) as the strongest descriptor of humic DOM. It exhibited strong positive correlations with $SUVA_{254}$, a_{280}, a_{350} and HIX, as well as strong negative correlations with BIX and f_4/f_5. Total fluorescence (IF_{tot}) correlated positively

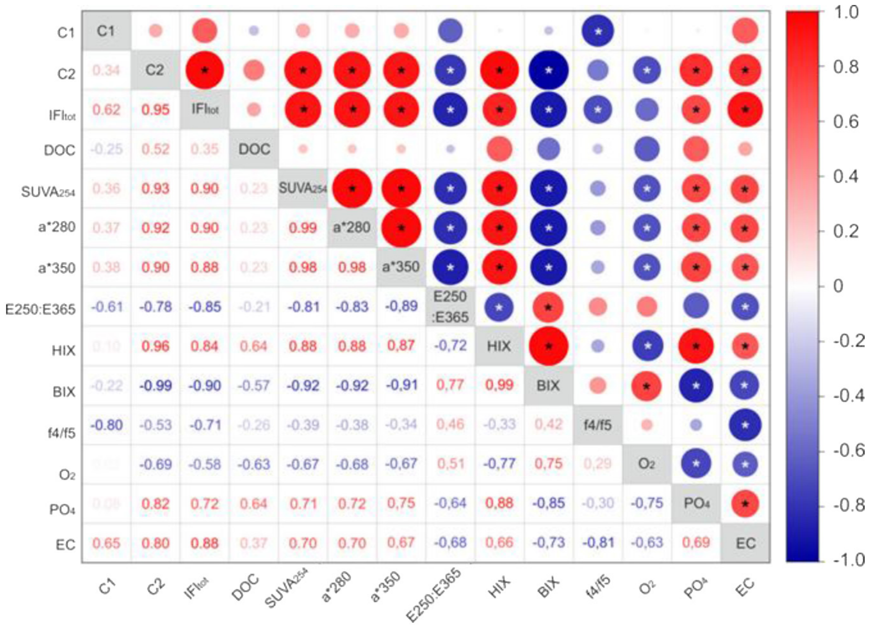

Fig. 6. Correlations between analyzed variables. The numbers denote values of Pearson's correlation coefficients; the asterisk denotes significance at a level of p<0.05

with $SUVA_{254}$, a_{280} and EC, suggesting that it increases with DOM aromaticity and water mineralization. The strong correlation between IF_{tot} and EC (r=0.88) indicates that ionic enrichment, likely associated with nitrogen and phosphorus-rich inputs, enhances DOM fluorescence. This is consistent with recent findings on nutrient – DOM interactions in eutrophic systems.

CONCLUSIONS

This study demonstrates pronounced spatial heterogeneity in the quantity and composition of DOM across the Lake Świdwie catchment, driven by contrasting hydrological settings and land-use patterns. The Gunica River transported low-aromatic, freshly produced autochthonous DOM, whereas the Struga Żurawia and the Bolków-Łęgi Canal delivered highly humified, aromatic, nutrient-enriched allochthonous material. The Mała Gunica was an intermediate system, shaped by both natural processes and human activity.

Optical indices ($SUVA_{254}$, a_{280}, a_{350} and E_{250}:E_{365}) and fluorescence-based parameters (BIX and HIX) consistently differentiated between these sources of DOM, revealing clear gradients in aromaticity, molecular weight and humification. PARAFAC modelling identified two dominant fluorophore groups: a microbially derived, less humified component (C1), and a humic-like, aromatic component (C2). The spatial distribution of these groups closely reflected the characteristics of the catchment.

Multivariate analyses (CCA, hierarchical clustering and Pearson correlations) provided strong statistical support for these patterns, highlighting nutrient enrichment, conductivity and the degree of humification as the main drivers of DOM variability. The strong positive relationship between total fluorescence and conductivity suggests that ionic enrichment, likely linked to nitrogen- and phosphorus-rich inputs, enhances DOM optical activity.

Overall, the findings highlight the sensitivity of small, shallow eutrophic catchments to natural and human-induced pressures. Combining UV-Vis spectroscopy, fluorescence EEMs and multivariate statistics was highly effective in identifying DOM sources and transformation pathways, providing valuable insights into carbon cycling during the post-growing season.

Classical 3D fluorescence spectra are particularly informative when sample numbers are limited, as they preserve full spectral detail, including peak positions and shifts in spectra. While powerful for analysing larger datasets, PARAFAC reduces spectral complexity. Using both approaches together provides a more comprehensive interpretation of fluorescence data by integrating high spectral resolution with robust component isolation.

Author contributions

L.M. – conceptualization, L.M., M.G., M.P. and J.D. – methodology and investigation, L.M., M.G. writing – original draft, M.P., L.M. – visualization, M.G. and E.H – supervision, writing – reviewing and editing, all authors. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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