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The impact of colluvial processes on the properties of organic and organic-mineral soils: a case study of a section of the river valley in the Izerskie Foothills, SW Poland

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Abstract

The use of soils in foothill areas and the drying of existing peatlands have, in many cases, led to denudation and degradation of the terrain. Research conducted in the Czarny Potok valley in the Izerskie Foothills examined the impact of colluvial processes on changes in soil structure and properties in extensive meadows, forests, and fallow land. Seven soil profiles were described, and 44 soil samples (including 24 organic samples) were collected for analysis of total organic carbon (TOC), total nitrogen (TN), water-extractable organic carbon (WEOC), and water-extractable total nitrogen (WETN). The soils were classified as Histosols and Gleysols (IUSS Working Group WRB, 2022) and as peat, mursh and gley soils (SPG6, 2019). In the surface layers of some soils, a low MtI and MtII medium mursh formation process was observed. Organic soils consisted of hemic and sapric materials; no fibric material was identified. Colluvial horizons were mainly composed of loam, silt loam and sandy loam. The results indicated that silting reduces the concentration of labile forms of organic matter (WEOC and WETN) in surface horizons compared to unsilted peat horizons. Low TOC/TN ratios and reduced concentrations of labile components in peat suggest increased biological activity and mineralisation of organic matter. In this case soil siltation did not increase their trophic status.

1. Introduction

Soils record both periods of intense contemporary environmental change and phases of stabilization (Palm et al., 2007). In mountainous areas and their foothills, shallow organic materials are often interbedded with mineral substrates (Schulte et al., 2006), resulting from near-surface processes (Thorp and Glanville, 2003) related to river-valley transformations and human activity (Borelli et al., 2020; Piaścik et al., 2001). The influence of aeolian processes on the formation of mineral horizons and their silting should also be considered (Fiałkiewicz-Kozieł et al., 2009). In peatland areas subjected to intensive drainage, the siltation of organic horizons is intensified by earthworks associated with the construction and maintenance of ditch networks (Bogacz et al., 2017; Verhoeven, 1992). These processes lead to the formation of soils whose layers can be distinguished based on varying silt content (Mama and Okafor, 2011).

The intensification of agriculture and forestry in mountainous and foothill zones (Glina et al., 2018; Bogacz and Roszkowicz, 2010) may degrade surface organic horizons (Andrzejczak et al., 2016), while siltation often alters their trophic status and habitat conditions (Glina et al., 2017). Mineral interlayers may also act as protective barriers for desiccating organic horizons, shielding them from atmospheric factors and slowing their mineralization (Smólczyński et al., 2021). The siltation of organic soils plays a significant role in shaping the carbon and nitrogen cycles in both aquatic and terrestrial ecosystems (Udom and Ogunwole, 2015). The accumulation of fine mineral particles affects oxygen availability (Kristensen, 2000), microbial activity (Fenchel et al., 2012), and the rate of organic matter mineralization (Sjöström et al., 2022).

Depending on the stage of siltation, this process can either promote the release of dissolved carbon and nitrogen compounds – water-extractable organic carbon (WEOC) and water-extractable total nitrogen (WETN) – or contribute to their stabilization through the formation of organo-mineral complexes (Fatima et al., 2023). Consequently, siltation may both stimulate and inhibit the mineralization of soil organic carbon (TOC), depending on the extent of sediment accumulation and prevailing environmental conditions (Zhong et al., 2024). Mineral interbedding has been shown to effectively protect organic soils in the young glacial landscapes of north-eastern Poland from degradation (Kalisz et al., 2021).

The Izerskie Foothills region contains relatively few bogs and fens, which together cover only about 1% of the area. The landscape is dominated by small peatlands—typically less than 10 ha in size and with a maximum depth of about 1 m (Dembek, 2001). Most peatlands have been drained using open-ditch systems and partially converted into meadows and pastures. Due to their valley setting, many organic soils, or their remnants, are influenced by adjacent slopes that have been intermittently or long-term used as arable land. Increased erosion is characteristic of this loess-dominated landscape (Loba et al., 2020). Silt-sized particles deposited on organic horizons either enrich the peat with mineral material (Sowiński et al., 2015) or form distinct layers of varying thickness (Orzechowski and Smólczyński, 2002). These processes significantly influence both the rate and pathways of organic matter transformation (Kalisz et al., 2021).

The aim of this study was to present changes in the characteristics of organic and organic-mineral soils under the influence of siltation processes in the valley areas of the Izerskie Foothills. In particular, the study aimed to assess both total and labile forms of organic carbon and nitrogen in peatlands affected by geomorphic processes intensified by human activity.

2. Materials and methods

The research was conducted in two sections of the Czarny Potok valley near the villages of Giebułtów and Orłowice, located in the Izerskie Foothills (Figs. 1–2). The Izerskie Foothills,

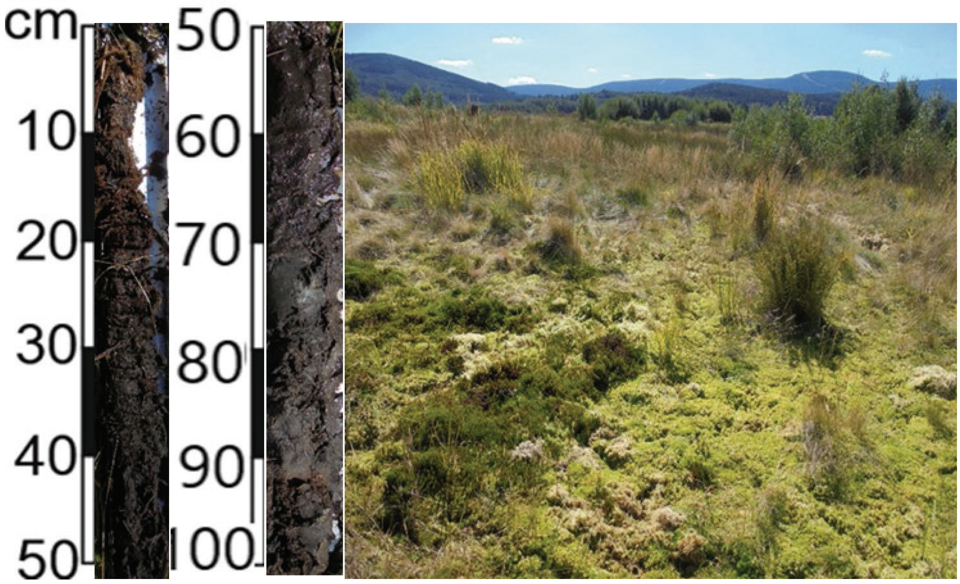


Fig. 1. Landscape in Orłowice transects and selected soil profiles: a) 0–50 cm, b) 50–100 cm

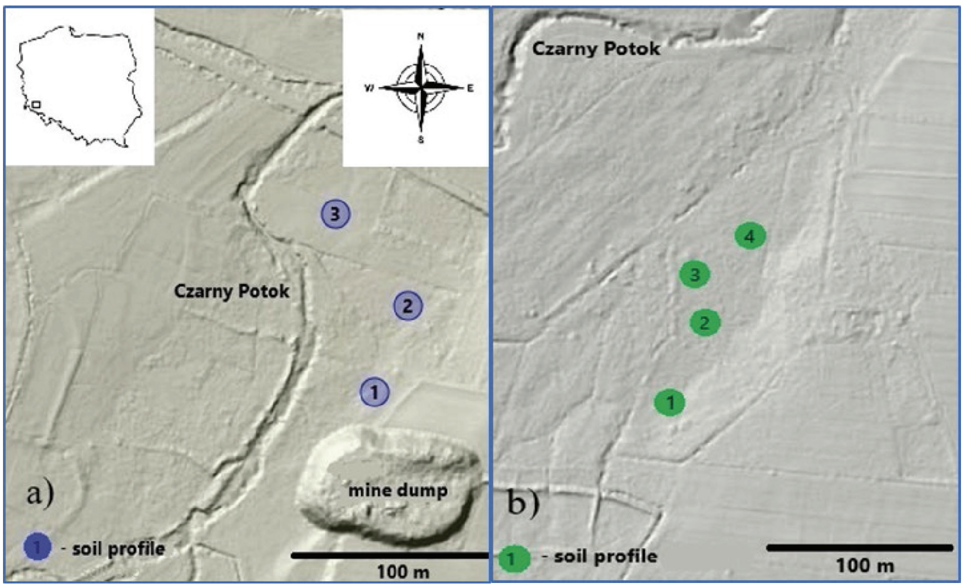


Fig. 2. Soil samples collection points of the a) Giebułtów, b) Orłowice transects

one of the oldest parts of the Sudetes, form part of the Karkonosze–Jizera Block, which belongs to the Czech Massif and the Western Sudetes. The area is composed mainly of metamorphic rocks, including gneisses, mica schists, and amphibolites, while its marginal zones feature igneous rocks, primarily granite. In depressions and sinkholes of the Izerskie Foothills, conglomerates, sandstones, and mudstones are also present. These foothills have undergone intensive tectonic and metamorphic processes, as well as reshaping by glaciers and fluvial activity during the Quaternary period. The studied area was influenced by both the San and Odra glaciations (Klimaszewski, 2005). Orłowice and Giebułtów are located at elevations of 396–399 m and 342–349 m a.s.l., respectively. The valley is filled with organic and organic-mineral substrates (Table 1) and is surrounded by loess deposits, which give rise to the formation of Luvisols and Cambisols (Polish Soil Classification, SGP6, 2019).

The average temperature between 2011 and 2020 was 9.1°C, and annual rainfall rarely exceeded 700 mm (Pawelec and Wereski, 2022). In the valley areas of the Izerskie Foothills, meadow communities cover nearly 93% of the area. These are primarily fresh meadows (*Arrhenatheretalia*), and to a lesser extent, variable-humid meadows (*Molinietalia*), which develop on dry, low peatlands (Kloss, 2007). A notable rarity in the foothill areas of the Sudetes is the presence of small fens (Wasiak et al., 2013), which are also found at the Giebułtów and Orłowice sites. In lower, wetter areas, enclaves of *Caricetum sp.* can be found (Matuszkiewicz, 2001). Rush vegetation occurs along the shores of small anthropogenic retention reservoirs scattered throughout the valley, often located at former peat extraction sites (Geoportal.gov.pl). Part of the wetland area within Orłowice (profiles 3 and 4) is covered by *Betula pubescens*, with the participation of *Vaccinium myrtillus*, *Eriophorum vaginatum*, and well-developed patches of *Sphagnum* sp. (Matuszkiewicz, 2001).

One of the well-known valley peat bogs near the study area is the Izera Valley peatlands complex in the Izerskie Mountains, formed under specific geomorphological (Traczyk and Migoń, 2000) and climatic conditions (Sobik and Błaś, 2010). The development of transitional and raised bogs began in the Preboreal (~11,500 years BP), with peat thickness typically reaching 1–3 m (Jóža and Vonička, 2004; Kaiser et al., 2021). Mineral silt, sand, and gravel layers indicate water erosion (Bogacz, 2005; Kaiser et al., 2025), while soil structure reflects human activity since the Middle Ages, including shepherding, forestry, metallurgy, and peat extraction (Lisowska and Jaworski, 2021; Nowak et al., 2023). The peatlands exhibit various developmental stages (Tołpa, 1949): early and mid-Holocene *Sphagnum* peat formation, followed by raised bog development dominated by *Carex* sp. during valley drainage, and finally the present stage, characterized by halted *Sphagnum* peat growth and coverage by spruce forests and dwarf pine (Potocka, 2000; Tomaszewska, 2004).

Seven soil profiles were prepared based on boreholes drilled with an Instorf auger, and 44 soil samples were collected (21 from the Giebułtów transect and 23 from the Orłowice transect), including 25 organic samples. Soil profiles were described according to the Polish Soil Classification (SGP6, 2019) and the WRB (IUSS Working Group WRB, 2022), with horizon colours determined using the Munsell Soil-Color Chart (2018).

Table 1
Profile location, land use and soil types

Profile	Altitude (m a.s.l.)	Coordinates	Inclination (°)	Land use	SPG6, 2019	IUSS Working Group WRB, 2022
Giebułtów 1	349	N 50°58’17.2” E 15°21’59.6”	2	fallow	Gleba torfowa, murszowa	Dystric Sapric Histosols (Drainic, Siltic, Fluvic, Gleic, Mineralic)
Giebułtów 2	347	N 50°58’19.9” E 15°22’1.0”	2	fallow	Gleba torfowa, murszowa	Dystric Hemic Histosols (Drainic, Siltic, Fluvic, Gleic)
Giebułtów 3	342	N 50°58’22.6” E 15°21’57.3”	1	meadow	Gleba torfowa, natorfowa	Distric Sapric Histosols (Drainic, Siltic, Fluvic, Gleyic)
Orłowice 1	399	N 50°56’23.8” E 15°20’47.5”	2	meadow	Gleba gruntowo--glejowa, torfowa	Eutric Histic Gleysols (Drainic, Siltic, Fluvic)
Orłowice 2	398	N 50°56’45.4” E 15°21’14,4”	3	meadow	Gleba torfowa, murszowa	Eutric Sapric Histosols (Drainic, Siltic, Fluvic, Mineralic)
Orłowice 3	397	N 50°56’46.6” E15°21’15.5”	2	forest	Gleba murszowa, saprowa	Eutric Sapric Histosols (Drainic, Siltic, Fluvic, Gleic.
Orłowice 4	396	N 50°56’25.9” E 15°20’54.2”	2	forest	Gleba torfowa, saprowa	Eutric Sapric Hemic Histosols (Rheic, Drainic)

Peat decomposition was assessed using the half-syringe method based on rubbed fibre (RF) and SPEC methods, enabling peat type classification. The pyrophosphate index (IP) was determined from extract colour (Lynn et al., 1974). Measurements were made using manholes and drainage pipes (Willis and Weight, 2019). Soil water extracts were prepared according to the procedure proposed by Kot et al. (2025). Ten grams of soil material were mixed with 100 ml of Millipore water and shaken for 30 minutes on a rotary shaker. The extracts were then filtered through qualitative cellulose filters (MUNKTELL-FILTRAK), followed by filtration through 0.45 μm polyether sulfone (PES) membrane filters pre-washed with Millipore water. WEOC was determined via infrared detection of CO_2, while WETN was measured by chemiluminescence detection of NO_x using the Enviro TOC analyser (Elementar Analysen Systeme GmbH, Germany). Ash content (A) was determined by combustion in a muffle furnace at 450°C for six hours (Hobbs, 1986). Specific density (d) and volumetric density (dv) of organic formations were calculated using regression equations (Okruszko, 1971):

$$d = 0.001 \cdot A + 1451, \qquad dv = 0.004 \cdot A + 0.0913$$

Total porosity (TP) was calculated from d and dv values. The granulometric composition of mineral horizons was determined using the Bouyoucos aerometric method modified by Casagrande and Prószyński. In high-humus colluvial samples, organic matter was removed with hydrogen peroxide prior to analysis. In fresh samples, pH in H_2O and KCl was measured potentiometrically at a 1:2.5 ratio. The presence of mursh horizons was verified using the water absorption index (W1) by Gawlik (1992a, 1992b, 2000).

In air-dried samples, TOC and TN were determined by gas analysis using a Vario Macro Cube analyser. Exchange acidity (KA) was measured by the Sokolow method, while basic cations (BS) were extracted with 1 mol·dm^{-3} CH_3COONH_4 (pH 7.0). Effective cation exchange capacity (CECe) was calculated from KA and the sum of base cations (BS). Soil classification was performed according to the Polish Soil Classification (SGP6, 2019) and the World Reference Base for Soil Resources (IUSS Working Group WRB, 2022).

Normality was tested using the Shapiro–Wilk test and was not confirmed for most variables. Therefore, Spearman's rank correlation was applied (n = 44), with significance set at $p < 0.05$. Statistical analyses were performed using Statistica 13 (StatSoft Inc., 2015).

3. Results

3.1 Soil morphology

The organic soils of the Giebułtów transect contained mineral interlayers several to over a dozen centimetres thick (Table 2). Strong redoximorphic features were observed, with intensity increasing in deeper, wetter horizons. Organic horizons showed amorphous, amorphous-fibrous, and fibrous structures, while mineral horizons were dominated by granular and angular blocky structures. Organic-rich surface horizons locally exhibited bioturbation traces. Identified diagnostic horizons included histic horizons according to WRB (IUSS Working Group WRB, 2022) and murszik horizons according to the Polish Soil Classification (SGP6, 2019; Łachacz et al., 2024), occurred locally and the low (MtI) mursh formation process. Mursh material in both transects showed a granular sod-mursh structure in upper parts and granular structure with loose humified fibres below. During the study period, groundwater levels in Giebułtów ranged from 30 to 70 cm below ground level (Table 3). In the Orłowice transect, mineral interlayers were less frequent, the relative amount of water was higher (Table 2), and groundwater levels ranged from 5 to 30 cm. Fibrous and amorphous-fibrous structures were more common, mineral horizons showed angular blocky structure, and no bioturbation was observed (Tables 2 and 3). Murshic main soil qualifier, occurred in one profile and showed low (MtI) and medium (MtII) mursh formation stages, with Z1-type grainy mursh (Okruszko and Ilnicki, 2003). Mineral horizons in both transects were dominated by coarse silt (0.05–0.02 mm), with sand prevailing in some samples. No coarse material (>2 mm) was found (Table 2). Clay content remained below 20%. Texturally, the deposits were classified mainly as loam, locally as silt loam or sandy loam. Grain-size variability was greater in the Giebułtów profiles (Fig. 3).

Table 2
Morphological parameters of soils in Giebałtów and Orłowice

Profile	Horizon	Depth (cm)	Color moist	Structure type	Wetness category	Horizon boundary	Redox mottles	Redox concentr.	Soil fauna	WRB horizon
Giebułtów 1	M	0–10	10YR 3/1	fibrous	moist	A, S	–	–	–	murshic
	G1	10–32	5Y 2.5/1	angular	moist	A, S	ox	–	–	gleic
	Oa1	32–58	10YR 3/1	amorphic	moist	A, S	–	–	–	histic
	G2	58–72	10YR 5/1	angular	moist	A, S	ox/red	Fe	–	gleic
	Oa2	72–84	10YR 3/1	amorphic	wet	A, S	–	–	–	histic
	G3	84-100	10Y 6/1	angular	wet	-	red	Fe	–	gleic

Table 2 – continue

Profile	Horizon	Depth (cm)	Color moist	Structure type	Wetness category	Horizon boundary	Redox mottles	Redox concentr.	Soil fauna	WRB horizon
Giebułtów 2	M	0–12	10YR 2/1	amorphic	moist	C, S	–	–	–	murshic
	Oa2	12–27	10YR 2/2	amorphic	moist	A, S	–	–	–	histic
	G1	27–33	10YR 2/1	angular	wet	A, S	ox/red	Fe	–	gleic
	Oe1	33–54	10YR 2/1	fibrous	wet	C, S	–	–	–	histic
	Oe2	54–68	5YR 2.5/2	fibrous	wet	C, S	–	–	–	histic
	Oe3	68–91	5YR 2,5/1	fibrous	wet	C, S	–	–	–	histic
	Oe4	91–97	5Y 3/2	fibrous	wet	C, S	–	–	–	histic
	Oe5	97–118	10YR 4/1	fibrous	wet	A, S	–	–	–	histic
	G2	118–120	10YR 4/1.5	angular	wet	-	red	Fe	–	gleic
Giebułtów 3	A	0–19	10YR 2/1	grainy	moist	A, S	–	–	+	-
	G1	19–32	10YR 4/1	angular	moist	A, S	ox/red	Fe	+	gleic
	Oa	32–60	10YR 2/2	amorphic	wet	A, S	–	–	–	histic
	G2	60–85	10YR 4/1	angular	wet	A, S	red	Fe	–	gleic
	Oa2	85–92	10YR 3/2	amorphic	wet	C, S	–	–	–	histic
	Oe	92–100	10YR 2/2	fibrous	wet	-	–	–	–	histic
Orłowice 1	M	0–19	10YR 2/1	amorphic	moist	C, S	–	–	–	murshic
	Oa2	19–30	10YR 2/2	amorphic	moist	A, S	–	–	–	histic
	G1	30 - 35	10YR 4/1	angular	wet	A, B	ox/red	Fe	–	gleic
	G/O	35–62	10YR 4/1	angular	wet	A, B	ox/red	Fe	–	gleic
	G2	62–70	10YR 4/2	angular	wet	C, S	red	Fe	–	gleic
	G3	70–82	10YR 5/1	angular	wet	A, S	red	Fe	–	gleic
Orłowice 2	M	0–20	10YR 2/2	grainy	moist	A, S	–	–	+	murshic
	G1	20–32	10YR 5/1	angular	moist	A, B	ox	–	–	gleic
	G/O	32–40	10YR 4/1	angular	wet	A, B	ox/red	Fe	–	gleic
	Oa	40–60	10YR 2/1	amorphic	wet	A, S	–	–	–	histic
	G2	60–80	10YR 7/2	angular	wet	C, S	red	Fe	–	gleic
	G3	80–100	10YR 6/1	angular	wet	-	red	Fe	–	gleic
Orłowice 3	M	0–22	10YR 3/1	grainy	wet	A, S	–	–	+	murshic
	Oa1	22–35	10YR 4/2	amorphic	wet	C, S	–	–	–	histic
	Oa2	35–60	10YR 3/2	amorphic	wet	C, S	–	–	–	histic
	Oa3	60–70	10YR 2/1	amorphic	wet	C, S	–	–	–	histic
	Oa4	70–80	10YR 3/3	amorphic	wet	-	–	–	–	histic
Orłowice 4	Oe1	0–13	10YR 3/2	fibrous	wet	C, S	–	–	–	histic
	Oe2	13–30	10YR 4/3	fibrous	wet	A, S	–	–	–	histic
	Oa1	30–65	10YR 4/2	amorphic	wet	C, S	–	–	–	histic
	Oa2	65–75	10YR 3/3	amorphic	wet	C, S	–	–	–	histic
	Oa3	75–85	10YR 2/2	amorphic	wet	C, S	–	–	–	histic
	Oa4	85–95	10YR 2/1	amorphic	wet	-	–	–	–	histic

Explanation: ox – oxidation, red – reduction, A – abrupt, B – boundary, C – clear, S – sharp.

Table 3
Physicochemical properties of soils in Giebałtów and Orłowice

Profile	Horizon	Depth (cm)	Ground-water table depth (cm)	pH H_2O	TOC (g kg^{-1})	TN (g kg^{-1})	TOC:TN	WEOC (mg kg^{-1})	WETN (mg kg^{-1})	WEOC:WETN	IP	W_1	RF (%)	Ash (%)	d (g cm^{-3})	dv (g cm^{-3})	Pc (%)
Giebułtów 1	M	0–10	30	4.5	267.4	14.8	18.0	286	6.09	47.0	3	0.60	16	49.0	0.29	1.99	85.4
	Cg1	10–32		4.6	94.85	3.16	30.0	65.6	2.89	22.7	–	–	–	–	–	–	
	Oa	32–58		4.8	264.5	15.4	17.1	102	2.25	45.3	2	–	13	50.0	0.29	2.00	85.5
	Cg2	58–72		5.1	72.96	1.85	39.4	30.1	1.75	17.2	–	–	–	–	–	–	
	Oa1	72–84		5.0	185.9	6.95	26.7	82.3	2.14	38.5	3	–	1	69.5	0.37	2.21	83.2
	Cgg	+ 84		5.4	22.93	0.26	87.4	15.9	1.71	9.30	–	–	–	–	–	–	
Giebułtów 2	M	0–12	50	4.2	255.3	13.6	18.7	290	5.04	57.5	3	0.58	12	51.9	0.30	2.02	85.1
	Oa1	12–27		4.4	193,1	9.39	20.6	97.8	4.13	23.7	3	–	12	68.2	0.36	2.20	83.6
	Oa2	27–33		4.9	124.3	3.94	31.5	70.0	2.50	28.0	2	–	10	76.5	0.40	2.29	82.5
	Oe1	33–54		3.6	428.5	17.4	24.6	233	5.14	45.3	5	–	13	20.5	0.17	1.68	89.9
	Oe2	54–68		2.9	399.9	15.4	25.9	459	4.86	94.4	5	–	20	22.6	0.18	1.70	89.4
	Oe3	68 - 91		3.0	406.1	14.7	27.6	648	5.55	117	5	–	14	20.6	0.17	1.68	89.9
	Oe4	91–97		3.3	341.1	15.9	21.5	204	3.61	56.5	5	–	9	39.7	0.25	1.89	86.8
	Oe5	97–118		3.3	396.0	17.1	23.2	348	7.45	46.7	4	–	27	28.5	0.20	1.76	88.6
	Cgg	+ 118		3.1	33.3	0.85	39.0	74.3	3.96	18.8	–	–	–	–	–	–	
Giebułtów 3	A	0–19	70	4.8	97.7	5.11	19.1	189	4.20	45.0	–	–	–	–	–	–	
	Gg1	19–32		4.67	74.4	3.48	21.4	79.7	6.83	11.7	–	–	–	–	–	–	
	Oa	32–60		4.5	206.7	8.15	25.4	89.7	2.93	30.6	3	–	9	43.5	0.26	1.93	86.5
	Cgg1	60–85		5.2	57.3	1.76	32.5	40.0	5.32	7.52	–	–	–	–	–	–	
	Cgg2	85–92		5.0	76.5	3.06	25.0	42.4	4.43	9.57	–	–	–	–	–	–	–
	Cgg3	92–100		4.9	66.5	2.45	27.2	71.3	3.08	23.1	–	–	–	–	–	–	–
Orłowice 1	M	0–19	30	4.6	140.2	4.83	29.0	71.8	3.74	19.2	1	0.57	8	78.0	0.40	2.31	82.7
	Cg1	19–30		4.4	110.0	3.48	31.6	57.4	4.22	13.6	–	–	–	–	–	–	–
	Cg2	30–35		4.4	82.13	2.43	33.8	52.7	2.62	20.1	–	–	–	–	–	–	–
	Cgg1	35–62		4.4	56.93	1.56	36.4	33.4	1.48	22.6	–	–	–	–	–	–	–
	Cgg2	62–70		4.6	62.10	1.56	36.4	34.9	1.65	21.1	–	–	–	–	–	–	–
	Cgg3	70–82		4.5	38.69	1.49	26.0	30.3	2.76	11.0	–	–	–	–	–	–	–
Orłowice 2	M	0–20	20	3.6	144.0	5.51	26.1	231	5.27	43.8	1	0.55	20	70.6	0.37	2.23	83.4
	Cg1	20–32		3.8	40.29	1.25	32.2	52.4	3.50	15.0	–	–	–	–	–	–	–
	Oa	32–40		3.7	200,0	7.03	28.5	75.7	3.24	23.4	3	–	10	68.0	0.36	2.20	83.6
	Cgg1	40–60		3.9	87.46	4.20	20.8	78.0	2.22	35.1	–	–	–	–	–	–	–
	Cgg2	60–80		4.0	40.32	1.14	35.4	35.2	3.46	10.2	–	–	–	–	–	–	–
	Cgg3	+ 80		4.0	21.16	0.26	82.3	22.4	2.97	7.5	–	–	–	–	–	–	–
Orłowice 3	M	0–22	10	4.1	242.3	9.63	25.2	248	6.32	39.2	1	0.50	8	48.3	0.28	1.98	85.8
	Oa1	22 - 35		3.5	378.6	14.0	27.0	143	4.72	30.3	2	–	5	33.5	0.22	1.82	87.9
	Oa2	35–60		3.6	400.7	13.8	28.9	177	4.57	38.7	3	–	6	23.4	0.18	1.71	89.5
	Oa3	60–70		3.6	432.7	15.0	28.8	299	5.17	57.8	3	–	5	19.6	0.17	1.67	89.8
	Oa4	70 - 80		3.6	417.4	13.3	31.4	433	5.50	78.7	3	–	10	21.9	0.18	1.69	89.3

Table 3 – continue

Profile	Horizon	Depth (cm)	Ground-water table depth (cm)	pH H_2O	TOC (g kg^{-1})	TN (g kg^{-1})	TOC: TN	WEOC (mg kg^{-1})	WETN (mg kg^{-1})	WEOC: WETN	IP	W_1	RF (%)	Ash (%)	d (g cm^{-3})	dv (g cm^{-3})	Pc (%)
Orłowice 4	Oe1	0–13	5	3.8	319.0	16.2	19.7	516	5.67	91.0	4	0.38	31	28.2	0.20	1.76	88.6
	Oe2	13–30		3.6	286.6	14.9	19.2	257	4.04	63.6	3	–	21	33.5	0.22	1.82	87.9
	Oa1	30–65		3.7	379.4	14.2	26.6	138	3.14	43.9	2	–	8	41.3	0.26	1.90	86.3
	Oa2	65–75		4.3	236.1	8.84	26.7	101	3.25	31.1	2	–	13	30.1	0.21	1.78	88.2
	Oa3	75–85		4.3	331.9	14.6	22.7	130	4.15	31.3	3	–	3	53.1	0.30	2.03	85.2
	Oa4	85 - 95		4.4	305.6	13.1	23.3	83.3	7.24	11.5	3	–	9	39.6	0.25	1.89	86.8

Explanation: IP – pyrophosphate index, RF – rubbed fibre, W_1 – water absorption index, d – specific density, dv – bulk density, Pc – total porosity, TOC – total organic carbon, TN – total nitrogen, WEOC – water-extractable total organic carbon, WETN – water-extractable total nitrogen.

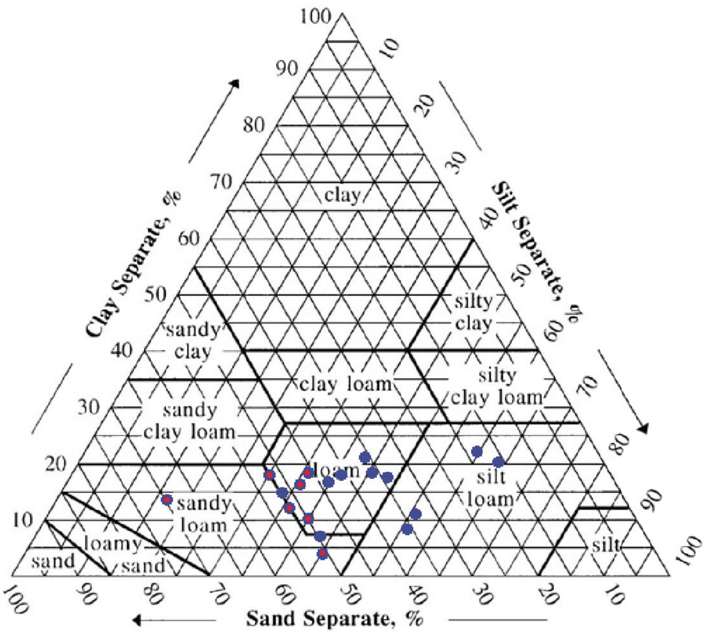


Fig. 3. Soil texture and samples horizons (Soil Taxonomy 1975)

3.2. Characteristic of organic horizons

The organic horizons were dominated by low sedge peats of the Magnocaricioni type, underlain by moss peats of the Bryalo-Parvocaricioni type, indicating a significant influence of groundwater on soil formation. At one highly waterlogged site in the Orłowice transect, transitional Minero-Sphagnioni moss peat occurred at the surface. The peat horizons showed strong siltation with sand and silt, which limited the reliability of RF-based assessments; however, combined methods indicated that most peats were highly decomposed (sapric), especially in the Giebułtów transect. In contrast, some horizons in the wetter parts of the Orłowice transect were classified as hemic (Soil Survey Staff, 1975). No fibric materials were identified. The relationship between peat humification and decomposition is shown in (Fig. 4). RF levels here are generally low, with varying IP values. This suggests the potential mobility of labile humus compounds in peatland environments.

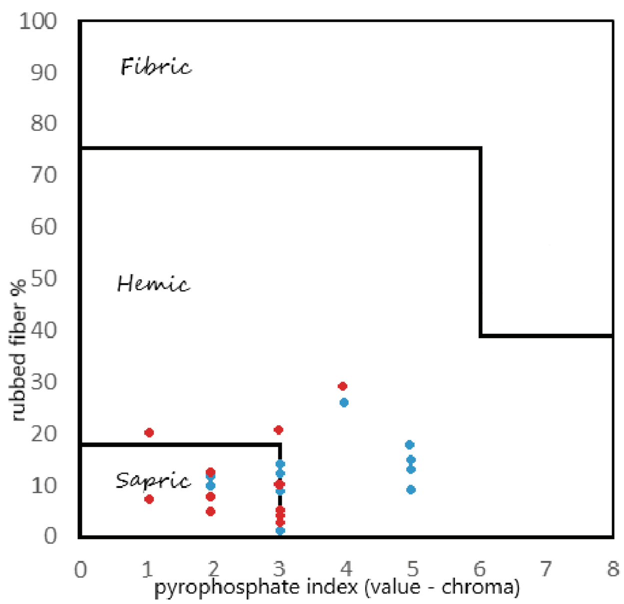


Fig. 4. Relationship between rubbed fibre (RF) content and pyrophosphate index (IP)

3.3 Physical properties of soil

The ash content in the organic horizons was generally high. Only one sample was classified as non-silted, containing less than 20% ash. A low degree of siltation (20–50% d.m.) was observed in more than half of the organic samples, most of which were located in the deeper sections of the soil profiles. Fewer than 30% of all organic samples were classified as highly silted, according to the classification by Okruszko (1973). Among the six surface organic horizons suspected of undergoing murshic transformation, five were diagnosed with a W1 index ranging from 0.51 to 0.60, which allowed them to be classified as slightly murshic (Gawlik 1992a, 1992b, 2000) (Table 3). The specific gravity of the organic horizons ranged from 1.68 to 2.29 g cm^{-3} in the Giebułtów soils and from 1.67 to 2.23 g cm^{-3} in the Orłowice soils, confirming a medium to high degree of siltation (Okruszko 1976). The organic horizons in the Orłowice transect were generally less silted and exhibited lower specific density. Total porosity (TP) in soils from both the Giebułtów and Orłowice sites did not exceed 90% of the soil volume (Table 3).

3.4. Chemical properties of soil

The reaction of the organic horizons at both sites ranged from acidic to strongly acidic. Soil pH measured in H_2O is the primary criterion for classifying organic soils as eutric or dystric according to WRB (IUSS Working Group WRB, 2022). All organic soils described in this study were classified as dystric (Table 3). No systematic decrease in pH with depth was observed, although abrupt changes in pH between adjacent horizons were common (Table 3). The distribution of pH values across different horizons is shown in Fig. 5.

In the studied valley sites, TOC ranged widely from 22.93 to 432.7 g kg^{-1}. Its content decreased with increasing soil siltation, from 432.7 g kg^{-1} in non-silted organic horizon to 124.3 g kg^{-1} in highly silted organic horizon. At both sites, TN ranged from 0.26 to 17.4 g kg^{-1}. Lower TN organic horizons were recorded in heavily silted horizons (3.94–14.6 g kg^{-1}), whereas higher values were found in non-silted horizons (up to 15.0 g kg^{-1}) (Table 3). The TOC/TN ratio, an important indicator of organic matter transformation, ranged from 17.1 to 31.4 in the organic horizons. Due to differences in siltation, the TOC/TN ratio ranged from 18.7 to 31.5 in highly silted horizons, compared to 28.8 in non-silted horizons. Figure 6 illustrates variation in the TOC/TN ratio in peat and mursh along the investigated transects. Strong variability in this parameter was observed in highly silted horizons (Table 3). Surface horizons generally showed lower TOC/TN values, indicating a higher degree of organic matter decomposition (Fig. 6). In the Orłowice and Giebułtów valleys, the TOC/TN ratio ranged from 13.1 to 19.1. In the colluvial mineral horizons, the measured TOC and TN values were sometimes very high or very low and showed large measurement errors; therefore, the TOC/TN is not presented in Fig. 6.

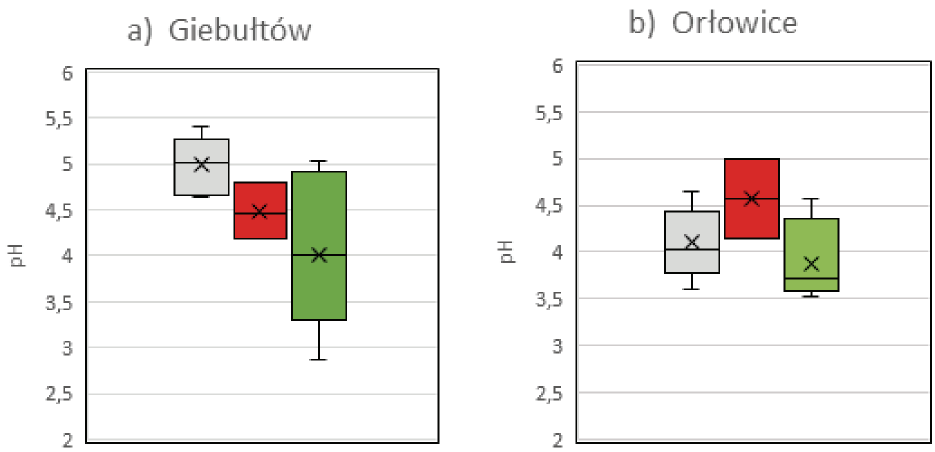
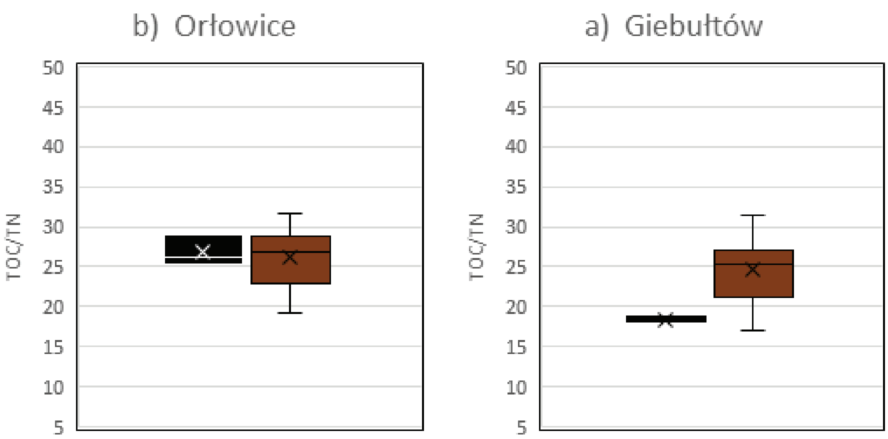


Fig. 5. pH in different soil horizons (mursh, peat, colluvium) in the: a) Giebułtów, b) Orłowice transects



mursh peat

Explanation on the graphs:
frame – standard deviation,
line – mine

Fig. 6. TOC/TN relationship in mursh, peat and colluvium horizons

WEOC concentrations ranged from 15.9 to 648 mg kg^{-1} in Giebułtów soils and from 22.4 to 516 mg kg^{-1} in Orłowice soils. The lowest WEOC values were observed in more decomposed, drier, and silted low-type peats, whereas higher concentrations occurred in less decomposed, unsilted, and deeper peat horizons. In many cases, WEOC values exceeded the typical range (10–60 mg L^{-1}) for water collected from drained peat soils, as reported by Thurman (1985). WETN values in the organic horizons ranged from 1.75 to 7.45 mg kg^{-1} in Giebułtów and from 1.48 to 6.32 mg kg^{-1} in Orłowice (Table 3).

An auxiliary indicator of trophic changes in organic and organic-mineral soils is the CECe value and the contribution of specific ions to this capacity. The Ca^{2+} content was the highest among all cations, especially in the soils at the Giebułtów site. In the Orłowice soils, Ca^{2+} levels rarely exceeded 20 cmol(+) kg^{-1}. The Mg^{2+} content also showed strong differences between horizons, particularly in the Giebułtów site, where values ranged from 0.42 to 11.74 cmol(+) kg^{-1}. High Na^{+} and K^{+} contents were generally comparable, except in several horizons in Orłowice, where their combined concentration occasionally exceeded 1 cmol(+) kg^{-1} (Table 4).

The effective sorption capacity (CECe) varied widely, ranging from 4.74 to 65.38 cmol(+) kg^{-1}, with particularly high variability in the Giebułtów soils. Consequently, base saturation

Table 4
Sorption properties in Giebułtów and Orłowice soils

Catena	Horizon	Depth (cm)	Ca^{+2}	Mg^{+2}	K^{+}	Na^{+}	S	KA	CECe	BS %
			cmol(+)kg^{-1}							
Giebułtów 1	M	0–10	10.11	3.76	0.09	0.54	14.5	2.02	16.52	87.8
	Cg1	10–32	12.57	2.82	0.14	0.40	15.93	1.14	17.07	93.3
	Oa1	32–58	4.92	2.22	0.48	0.37	7.99	1.32	9.31	85.8
	Cg2	58–72	14.59	5.92	0.17	0.55	21.23	0.62	21.85	97.2
	Oa2	72–84	21.26	0.78	0.11	0.64	22.79	1.00	23.79	95.8
	Cgg	84–100	4.00	8.27	0.40	0.19	12.86	0.32	13.18	98.0
Giebułtów 2	M	0–12	21.24	7.16	0.46	0.37	29.23	6.86	36.09	81.0
	Oa1	12–27	20.96	5.52	0.05	0.49	27.02	4.60	31.80	85.0
	Oa2	27–33	23.33	6.15	0.06	0.55	30.09	3.00	33.09	90.9
	Oe1	33–54	9.12	11.74	0.05	0.18	21.09	8.95	30.04	70.2
	Oe2	54–68	1.82	5.70	0.09	0.07	7.68	40.00	47.68	16.1
	Oe3	68–91	10.37	3.57	0.24	0.40	14.58	43.85	58.44	24.9
	Oe4	91–97	10.11	4.61	0.27	0.24	15.23	22.00	37.23	40.9
	Oe5	97–118	20.30	11.05	0.31	0.70	32.36	33.02	65.38	49.5
Giebułtów 3	A	0–19	11.03	1.09	0.37	0.32	12.81	8.22	21.03	60.9
	Cg1	19–32	3.18	2.25	0.29	0.29	6.01	1.96	7.97	76.4
	Oa	32–60	15.57	4.71	0.31	0.27	20.86	9.71	30.57	68.2
	Cgg1	60–85	2.22	2.04	0.11	0.07	4.42	0.32	4.74	93.2
	Cgg2	85–92	18.84	3.18	0.31	0.27	22.60	0.70	23.30	97.0
	Cgg3	92–100	9.08	5.62	0.17	0.33	15.20	0.89	16.09	94.5
Orłowice 1	M	0–19	4.33	2.25	0.18	0.16	6.92	13.1	20.02	34.6
	Cg1	19–30	19.78	0.72	2.06	1.84	24.40	0.83	25.23	96.7
	Cg2	30–35	3.31	1.98	0.27	0.27	5.83	1.60	7.43	78.5
	Cgg1	35–62	24.12	4.81	0.08	0.36	29.40	1.00	30.40	96.7
	Cgg2	62–70	6.61	1.76	0.10	0.23	8.70	2.35	11.05	79.2
	Cgg3	70–82	2.03	0.68	0.12	0.09	2.92	11.3	14.22	20.5
	Oe	82–100	9.12	11.74	0.05	0.16	21.09	4.56	25.65	82.2

Table 4 – contine

Catena	Horizon	Depth (cm)	Ca^{+2}	Mg^{+2}	K^{+}	Na^{+}	S	KA	CECe	BS %
			cmol(+)kg^{-1}							
Orłowice 2	M	0–20	4.10	1.09	0.12	0.09	5.30	8.20	13.50	39.2
	Cg1	20–32	4.53	1.30	0.15	0.16	6.14	8.76	14.90	41.2
	Oa	32–40	1.55	0.42	0.23	0.13	2.33	10.79	13.12	17.7
	Cgg1	40–60	7.83	9.17	0.04	0.13	17.17	12.88	30.05	57.1
	Cgg2	60–80	7.69	3.00	0.10	0.40	11.19	8.36	19.55	57.2
	Cgg3	80-100	5.48	2.75	0.27	0.19	8.69	6.07	14.76	58.9
Orłowice 3	M	0–22	5.90	2.89	0.25	0.25	9.29	5.20	14.49	64.1
	Oa1	22 - 35	6.87	1.98	0.24	0.28	9.37	13.74	23.11	40.5
	Oa2	35–60	7.85	1.07	0.22	0.31	9.45	22.76	32.21	29.3
	Oa3	60–70	4.49	1.70	0.16	0.19	6.98	13.31	20.29	34.4
	Oa4	70 - 80	4.40	1.60	0.14	0.18	6.32	29.38	35.70	17.7
Orłowice 4	Oe1	0–13	2.86	1.48	0.18	0.13	4.65	10.05	15.15	30.7
	Oe2	13–30	2.69	1.39	0.17	0.12	4.37	29.83	34.20	12.8
	Oa1	30–65	17.81	4.51	0.16	0.47	22.95	22.65	45.60	50.3
	Oa2	65–75	11.37	7.50	0.19	0.55	19.61	10.54	30.15	65.0
	Oa3	75–85	4.94	10.49	0.57	1.00	17.00	1.31	18.31	90.9
	Oa4	85–95	6.58	10.76	0.59	1.11	19.04	2.13	21.17	89.9

Explanation: (S) – sum of exchangeable cations (Ca^{+2}, Mg^{+2}, K^{+}, Na^{+}), KA – exchange acidity, CECe – effective cation exchange capacity, BS-cation base saturation

(BS) also varied considerably, from 12.8% to 98% (Table 4). The calculated BS values classified all soils in the Giebułtów site as eutrophic, whereas soils in the Orłowice site, due to spatial trophic variability within the valley, were classified as dystric. Despite such varied BS values all tested soils were classified as dystrophic.

4. Discussion

Peat material containing $CaCO_3$ may function as a buffer, limiting the acidification of deeper peat layers (Braun, 2010). Continuous saturation of peatlands stabilizes soil pH but, over time, may ultimately promote peat acidification (Kolka, 2015). Soils from peatland areas, particularly those in the young-glacial zone, are typically characterized by decreasing pH values with depth (Orzechowski and Smólczyński, 2002). However, this pattern was not observed in the valley soils of the Giebułtów and Orłowice sites (Table 5). This deviation may result from variations in sulphur content within waterlogged and strongly waterlogged horizons, as well as from periodic drying of these layers (Goblin and Wieder, 1992). Low pH values in soil horizons at both sites were accompanied by high contents of TOC, TN, and their water-soluble forms.

Total organic carbon content may vary widely, from 230 to 340 g kg^{-1} in heavily silted fen peats (Truba and Oleszczuk, 2014) to 405–535 g kg^{-1} in high-grass moss peats (Bogacz, 2005). Such variability is commonly associated with siltation and/or aeolian deposition of mineral material onto periodically forming organic horizons (Orzechowski and Smólczyński, 2002). Drainage of peatlands for agricultural use initiates oxidation of organic matter, leading to a decline in TOC content (Bojko and Kabała, 2016), which is currently a widespread negative effect of anthropogenic pressure on soil environments (Wertzel et al., 2012). In the surface horizons of the Giebułtów and Orłowice sites, TOC accumulation was favoured by low soil pH and relatively low ash content of organic formations (Table 3), which is consistent with findings by Cong et al. (2023) and Stolarczyk et al. (2017).

Total nitrogen content in peat horizons varies depending on the composition of organic residues, ranging from 4.10 g kg^{-1} in high-moss peats in Lithuania (Klavins et al., 2008) to 37.8 g kg^{-1} in fen peats in Poland (Sokołowska et al., 2011). In the organic and organic-mineral soils of the Czarny Potok Valley, increasing nitrogen content was accompanied by increasing organic carbon content. TN accumulation was also promoted by low soil pH (Table 5). The TN contents observed in this study are consistent with values reported by Gotkiewicz (1996) and are typical of lowland peat soils (Bayley et al., 2005).

The TOC/TN ratio is a useful indicator of organic matter transformation in peat soils (Lasota and Błońska, 2021). Similar relationships were reported by Ilnicki and Zeitz (2003) and

Table 5
Spearman correlation coefficients (p) for the tested soil parameters

Variable	Depth	pH	TOC	TN	TOC/TN	WEOC	WEON	CECe	RF
pH	–0.14								
TOC	0.20	–0.56							
TN	0.28	–0.54	0.60						
TOC/TN	–0.08	0.11	–0.35	–0.69					
WEOC	0.16	–0.56	0.78	0.89	0.63				
WEON	0.01	–0.46	0.49	0.53	–0.42	0.68			
CECe	0.26	–0.40	0.49	0.40	–0.19	0.46	0.17		
RF	–0.23	–0.28	0.02	0.37	–0.42	0.50	0.34	0.18	
ASH	–0.42	0.63	–0.89	–0.67	–0.08	–0.69	–0.45	–0.36	–0.20

Explanation: n=44, red colour – correlation coefficients p>0.05*

Kalisz et al. (2021). High TOC/TN ratios (approaching 20:1) are characteristic of poorly decomposed, slightly silted peat soils in fen habitats (Smólczyński et al., 2021). More strongly silted subsurface horizons exhibited values closer to 15:1—lower than in undecomposed peat but higher than in more mineralized horizons. Lower TOC/TN ratios (12:1–13:1), reported by Truba and Oleszczuk (2014), indicate advanced mineralization of horizons consisting of murszik horizon (SGP6, 2019). Other studies have shown that this ratio decreases with increasing secondary mineralization of horizons consisting of mursh material (Becher and Kalembasa, 2011). In the studied river valley of the Izerskie Foothills, TOC/TN values were lower in surface horizons (Table 5), although Smólczyński et al. (2021) reported no significant effect of siltation on this ratio in fen habitats.

One indicator of ongoing changes in variably moist and often destabilized organic soils is the content of WEOC and WETN (Freeman et al., 2001). Elevated concentrations of these fractions may reflect intensive peat decomposition caused by hydrological changes and increased oxygen availability (Clark et al., 2005). Mursh horizons showed a relatively high WEOC fraction compared to other organic horizons (Table 3), which is consistent with pronounced soil drying in areas dominated by herbaceous vegetation (Yarwood, 2018).

The highest WEOC contents were recorded in the most strongly waterlogged soils of the study area (profiles 3 and 4 at the Orłowice site), likely associated with plant communities dominated by *Sphagnum spp*. (Negassa et al., 2021). Medium-decomposed peat horizons exhibited higher WEOC contents than highly decomposed peat at both study sites, which appears atypical for this fraction (Vonk et al., 2015). The most important factor controlling WEOC content is therefore likely the botanical composition of peat material (Ritson et al., 2017).

Improper peatland use, such as overgrazing, can enhance the transfer of WEOC to surface waters (Worrall et al., 2007). Climate change and rising atmospheric CO_2 concentrations may further influence organic matter decomposition, as reflected in WEOC levels (Freeman et al., 2004). The WETN fraction generally responds to environmental drivers in a manner similar to WEOC (Kalbitz et al., 2000). In the study area, WETN contents in mursh horizons were slightly lower than in other organic horizons (Table 3), possibly due to faster warming of mursh material resulting from its distinct physical properties (Evans et al., 2006), particularly in the drier soils of the Giebułtów site.

Strong variation in WETN contents within mineral horizons (Table 3) may be related to differences in granulometric composition among profiles (Fig. 3), as previously suggested by Solinger et al. (2001). These findings highlight the importance of effective groundwater management in regulating nitrification and denitrification processes in valley peatlands (Voigt et al., 2020).

Variation in soil pH, particularly in strongly acidic and acidic soils, was likely driven by differences in waterlogging intensity and associated redox conditions (Zhou et al., 2022). The effective cation exchange capacity (CECe) of organic soils is generally high due to the abundance of organic matter rich in functional groups (Tan, 2003). The presence of colluvial horizons can substantially modify CECe within soil profiles. Colluvial material poor in organic matter and enriched in leached sand fractions reduces CECe (Tomasic et al., 2013), whereas horizons rich in clay minerals such as illite and montmorillonite may increase CECe, particularly under slightly acidic to neutral conditions (Painemann et al., 2000). Increased soil siltation, indicated by higher ash content, was associated with elevated CECe values (Table 5).

High contents of Na^+ and K^+ are uncommon in peat soils (Lisztwan and Korol, 1975). Changes in trophic status affected both individual horizons and entire transects and may be related to differences in the geochemistry of groundwater supplying various parts of the valley and to water mixing processes (Solovey and Jóźwiak, 2019). Higher CECe values at both study sites were favoured by increased TOC and WEOC contents. In contrast, higher soil pH values did not promote the accumulation of total carbon and nitrogen (Table 5).

Based on soil morphology and physicochemical properties, the soils were classified according to the Polish Soil Classification (SGP6, 2019) as sapric peat soils, hemic peat soils, earth-covered peat soils, murshic peat soils, and peaty gleysols (Kabała et al., 2019). According to the World Reference Base for

Soil Resources (IUSS Working Group WRB, 2022), the soils were classified as Histosols or Gleysols with appropriate qualifiers (Table 1). Soil siltation and the presence of mineral colluvial horizons are reflected by the mineralic qualifier in Histosols.

5. Conclusions

1. Colluvial processes in the Czarny Potok valley significantly influence soil properties and structure, leading to silting and the transformation of organic horizon.
2. Soil siltation involves a decrease in the content of readily available forms of carbon WEOC and nitrogen WETN in surface horizons compared to unsilted peat horizons.
3. Low TOC/TN ratio values and a reduced concentration of labile forms indicate increased biological activity.
4. The MtI and MtII stages of mursh formation process observed in the upper horizons of some soils indicate their progressive degradation and the transformation of the original peats.
5. Changes in land use and peatland drainage contribute to the degradation of organic soils.

Conflict of interest

The authors declare no conflict of interest. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. This research did not involve human or animal subjects.

Author Contributions

Adam Bogacz – Investigation, Methodology, Visualization, Writing. **Dariusz Gruszka** – Investigation, Methodology, Supervision, Visualization. **Aleksandra Loba** – Investigation, **Aleksandra Kot** – Investigation. **Beata Łabaz** – Investigation. **Magdalena Bednik-Dudek** – Investigation. **Michał Dudek** – Investigation. **Cezary Kabała** – Conceptualization, Investigation, Methodology. **Jarosław Waroszewski** – Conceptualization, Investigation, Methodology, Writing – Review and Editing. All authors read and approved the final manuscript.

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Wpływ procesów koluwialnych na właściwości gleb organicznych i organiczno-mineralnych: Studium przypadku odcinka doliny rzecznej na Pogórzu Izerskim

Słowa kluczowe

Zamulenie
Dolina rzeczna
Poziomy humusowe
Poziomy mineralne
Strefa podgórska

Użytkowanie gleb na obszarach podgórskich i przesuszenie istniejących tam torfowisk, doprowadziło w wielu przypadkach do denudacji i degradacji terenu. Prowadzone badania pokazują wpływ procesów koluwiacji na zmianę budowy i właściwości gleb w dwóch częściach doliny Czarnego Potoku na Pogórzu Izerskim, użytkowanych jako ekstensywne łąki, lasy oraz obszary odłogowane. Opisano 7 profili glebowych, z których pobrano 44 próbki glebowe (w tym 24 próbek organicznych) do analiz, miedzy innymi takich jak: całkowitych form węgla (TOC), azotu (TN), form wodno-rozpuszczalnych węgla (WEOC) i labilnych form azotu (WEON). Gleby klasyfikowano jako Histosols i Gleysols (IUSS Working Group WRB, 2022) oraz gleby torfowe, murszowe oraz glejowe (SPG6, 2019). W poziomach powierzchniowych niektórych gleb rozwinął się proces murszowy w stopniu słabym MtI lub średnim MtII. Gleby organiczne były zbudowane z materiałów hemic i sapric. Nie stwierdzono materiałów fibric. Poziomy koluwialne wytworzone były głównie z glin, glin piaszczystych oraz pyłów gliniastych. Rezultaty badań pokazały, że zamulenie wpływa na redukcję koncentracji labilnych form węgla i azotu w poziomach powierzchniowych w porównaniu do niezamulonych poziomów torfowych. Niskie wartości wskaźnika TOC/TN i niskie stężenia labilnych komponentów w torfie, sugerują wzrost aktywności biologicznej gleb i mineralizację materii organicznej. W tym przypadku zamulenie gleb nie prowadziło do wzrostu ich statusu troficznego.