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Origin, properties, and classification of organic soils in the Vistula Delta, northern Poland

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Abstract

The aim of this study was to present the origin and properties of organic soils occurring on the Holocene delta plain of the youngest geographical region in Poland – the Vistula Delta (Żuławy Wiślane, northern Poland). According to the Polish soil classification, the organic soils were represented by: (1) Murshic peat soils, hemic, (slightly silted), (OTmu), (2) Murshic peat soils, fibric, (strongly silted), (OTmu), (3) Sapric murshic soils (strongly silted), (OMsa), (4) Earth-covered peat soils, fibric, (OTnt), (5) Muddy soils, (OJmł), (6) Murshic gyttja soils, (OJgymu). The origin of these soils is closely related to the high variability of water conditions in the Vistula Delta, which favored the sedimentation of organic materials: peat, mud, and gyttja, as well as the variable intensity of river floods. As a result of these floods, mineral fluvial sediments either enriched organic deposits during the accumulation and decay phases or were deposited on their surface. The silting of the surface horizons of peat or mursh soils caused their compaction, a decrease in total porosity (including macropore volume), a reduction in water retention (pF 2.0), and a decline in plant-available water compared to the deeper peat horizons in the soil profiles. Increasing silting (as indicated by loss-on-ignition) in the studied soils was significantly positively correlated with the degree of soil saturation with calcium and potassium cations, as well as with the base saturation (BS), and negatively correlated with the hydrogen cation content in the sorption complex and with total exchangeable bases (TEB). The highest agricultural value is represented by the earth-covered peat soils, which are classified as class III grassland soils. Peat murshic soils, muddy soils, and gyttja soils represent grasslands of class IV, while murshic soils under arable use are classified as class IVa arable land.

1. Introduction

The Vistula Delta (Żuławy Wiślane) is located within the Gdańsk Coastal Region (Pobrzeże Gdańskie), northern Poland, which is a part of the South Baltic Coasts (Pobrzeża Południowobałtyckie), and covers an area of 174.2 thousand hectares (Kondracki, 2000).

The name Żuławy derives from the word 'żuł', which in the local dialect means 'plant sediment' formed in forested and swampy areas (Kowalik, 1976).

The area of the Vistula Delta forms a Holocene plain of uniform origin, shaped by the cumulative activity of rivers and by human technical interventions (Bertram, 1935; Augustowski, 1976). The southern part of the Vistula Delta is elevated from +5 to +10 m a.s.l. and gradually slopes northwards into a depression (Witek, 1965; Piaścik et al., 2000). Considering the hypsometry of the delta, two parts can be distinguished: the High Vistula Delta (Żuławy Wysokie), lying between +2.5 and +10.0 m a.s.l., and the Low Vistula Delta (Żuławy Niskie), lying below +2.5 m a.s.l., comprising sub-depression and depression areas located below sea level (Laskowski, 1961; Witek, 1965; Augustowski, 1976). The process of the Vistula Delta formation began about 6,000 years ago, during the Litorina period, when the course of the Vistula River changed from a westerly to a northerly direction. As a result, vast wetland (swamp) areas were formed, which over time began to dry up and became overgrown first with grass, and later forest vegetation (Cyberski and Mikulski, 1976).

The organic soils of the Vistula Delta stand out among other regions of Poland due to the deltaic nature of the mesoregion. The accumulation of organic deposits occurred as a result of terrestralization of shallow water bodies, accompanied by periodic river flooding, which deposited mineral alluvia. At the turn of the 13th and 14th centuries, the depression areas of the Vistula Delta contained water bodies covered with algae and largely overgrown with reeds and sedges, as well as alder swamp forests and peatlands (Witek, 1965; Kowalik, 1976).

The natural accumulation of organic deposits and soils was disturbed by human activity in the 14th century, and the intensity of drainage and reclamation works increased in the 17th century, following the arrival of Dutch settlers in the region (Bertram, 1935; Augustowski, 1976). To ensure the functioning of this deltaic plain located between land and sea, a mechanical-gravitational drainage system was constructed, serving both protective (anti-flood) and meliorative purposes. The history of the Vistula Delta is therefore one of over 700 years of human struggle against water. Through hydrotechnical works, such as river regulation, canal construction, and the establishment of flood protection structures, this area has been maintained in a condition that allows for its agricultural and settlement use (Cebulak, 1976; Kowalik, 1976).

The large variability of water conditions in the Vistula Delta has determined the diversity of wetland types, while sedimentation processes have modified peat formation and mud formation. Fluvial mineral deposits enriched organic soils or accumulated on their surface (Witek, 1965). As a result of these processes, the deltaic landscape of the Vistula River is characterized by a great diversity of organic formations, represented by peats of varying degrees of silting and decomposition, muddy alluvia, and gyttjas – mineral, mineral-organic, and organic (Smólczyński et al., 2000). At present, most organic soils in Poland, including those in the Vistula Delta, are in the decession phase and are undergoing mursh formation (murshing) (Łachacz et al. 2023). Their drainage and agricultural use contribute to changes in their properties (Gnatowski et al., 2010; Markiewicz et al., 2015) and degradation of the soil cover (Piaścik et al., 1990; Glina et al., 2016; Łachacz et al., 2023).

The aim of this study was to depict the origin, distribution, and properties of organic soils in the deltaic and depression areas of the Vistula Delta, including the criteria of the 6th edition of the Polish Soil Classification (2019).

2. Materials and methods

In the area of the Vistula Delta, a study of the organic soil cover was carried out, including 27 soil profiles. Among these soils, six representative ones were chosen and described in this paper. These profiles represented the following types of organic soils (1) Murshic peat soils, hemic, (slightly silted), (OTmu)*, Hemic Murshic Eutric Histosols (Hyperorganic)**, (2) Murshic peat soils, fibric, (strongly silted), (OTmu)*, Fibric Murshic Eutric Histosols**, (3) Sapric murshic soils (strongly silted), (OMsa)*, Murshic Hypereutric Histosols**, (4) Earth-covered peat soils, fibric, (OTnt)*, Fibric Murshic Eutric Histosols (Hyperorganic, Novic)**, (5) Muddy soils, (OJmł) *, Sapric Histosols (Limnic)**, (6) Murshic gyttja soils, (OJgymu)*, Murshic Sapric Hypereutric Histosols (Limnic)** (*Kabała et al., 2019; **IUSS Working Group WRB, 2022).

The studied soils contained varying amounts of organic matter and varying degrees of siltation. The content of organic matter was the base for the separation of the following soil groups within the studied population: mineral-humus formation (containing from 3% to 10% of organic matter), mineral-organic formations (10–20% of organic matter), strongly silted mursh (20–50% of organic matter) and slightly silted mursh (50–80% of organic matter) and peat formations (containing more than 80% of organic matter). The above classification was based on the mineral matter content according to Okruszko (1976, 1988).

Twenty four soil samples were collected into 100 cm^3 steel cylinders (undisturbed soil samples; in four replications) and into plastic bags for laboratory analyses. Selected physical and chemical properties were determined. The pH in H_2O and in 1 mol dm^{-3} KCl was determined by the potentiometric method, the content of organic matter (OM) and ash was determined on the base of loss-on-ignition at 550°C in a Lenton muffle furnace, total organic carbon (TOC) and total nitrogen (TN) contents were determined using a CN Vario Max Cube Elementar analyzer, the content of exchangeable base cations (Ca^{2+}, Mg^{2+}, Na^+, K^+) was determined in the extract of ammonium acetate – CH_3COONH_4 (1 mol dm^{-3}) at the pH of 7.0 (Van Reeuwijk, 2002) using iCAP 7400 ICP – OES Thermo Scientific spectrometer, hydrolytic acidity (H^+) was determined by the method of Kappen after extraction in barium chloride – $BaCl_2$ at the pH of 8.2. The cation exchange capacity (CEC) was calculated as the sum of total exchange bases (TEB – sum of base cations) and hydrolytic acidity (H^+).

Specific density (Sd) of organic formations was calculated using the equation of Okruszko (1971): Sd = 0.011 × A + 1.451, where A is the ash content [%]. The soil bulk density (Bd) was determined in undisturbed 100 cm^3 soil samples after drying them to a constant mass. Total porosity (TP) was calculated according to the equation:

$$TP = (Sd - Bd) \times Sd^{-1} \times 100\ (\%)$$

Soil water retention properties were determined using low-pressure (pF 2.0) and high-pressure (in pF 2.7 and pF 4.2) chambers. Water capacities (Wv/v) were examined at water potential of 98.10 hPa (pF 2.0), 490.50 hPa (pF 2.7) and 15 547.9 hPa (pF 4.2). The volume of the following soil pores and water capacities were calculated: macropores (total porosity – Wv/v at pF 2.0), micropores (Wv/v at pF 4.2), mesopores (Wv/v at pF 2.0 – Wv/v at pF 4.2). Mesopores are related to potential useful water retention because they contain water available to plants (AWC – available water capacity). Among AWC, readily available water capacity – RAWC (Wv/v at pF 2.0 – Wv/v at pF 2.7), and small pores available water capacity – SAWC (Wv/v at pF 2.7 – Wv/v at pF 4.2) were calculated (Zawadzki, 1973; Walczak et al., 2002).

The statistical analyses were performed using Statistica 13.1 software (StatSoft Poland). Principal component analysis (PCA) was applied to reveal the structure of relationships among the studied variables and among the studied soil formations. Since the variables are in disparate units, the data were standardized, and the principal components were calculated based on the correlation matrix.

3. Results and discussion

The organic soils of the Vistula Delta (Żuławy Wiślane) cover 9,476.0 ha, representing 5.5% of the mesoregion's surface area (Table 1). These soils occur mainly in depression areas, which occupy approximately 28% of the Vistula Delta and are situated, on average, from 0.5 to 0.9 m below sea level. Among the organic soils, peat soils and murshic peat soils predominate, covering about 2.7% of the delta's surface (Smólczyński et al., 2000). The largest complexes of these soils occur around Lake Drużno, south of Jegłownik, near Nowy Dwór Gdański, and between Pruszcz Gdański and Pszczółki (Fig. 1). The origin of muddy soils in the Vistula Delta is related to the accumulation of organic limnetic muds in shallow water (mainly oxbow lakes). Simultaneously, sedimentation of fine-grained material occurred. During floods, also mineral or mineral-organic sediments were accumulated as separate layers.

Table 1
Area of organic soils in the Vistula Delta

Soil unit	Area		
	ha	%*	%**
Peat and murshic peat soils	4704.0	49.6	2.7
Earth-covered peat and earth-covered murshic soils	1955.0	20.6	1.1
Muddy soils	778.0	8.3	0.5
Murshic gyttja soils	2039.0	21.5	1.2
Total	9476.0	100.0	5.5

* – in relation to organic soils, ** – in relation to all soils

Among the organic soils classified according to the Polish Soil Classification (SGP6) as murshic, slightly silted, and strongly silted peat soils, the thickness of murshic horizons reaches up to 30 cm, and these soils are under permanent grassland cover. Small areas are occupied by sapric and hemic murshic soils, with the murshic horizon reaching up to 36 cm in thickness, and they are used as arable land. Within the Vistula Delta, soils classified as strongly silted (with >50% ash content) are dominant. The mineral material consists of fine-grained alluvial silts and clays, with no perceptible sand grains by tactile assessment. The content of mineral matter in the surface murshic horizons of murshic peat soils ranged from 28.0% to 63.5% (Table 2), whereas the total organic carbon (TOC) content varied widely from 151.8 g kg^{-1} to 446.6 g kg^{-1}. The TOC/TN ratio ranged from 11.4 to 18.5 and was lower than in peat horizons. The parent material of these soils consists mainly of hemic and fibric reed peat, with a smaller share of sapric alder wood peat. The peat horizons are less silted with mineral material than the murshic ones, with mineral content ranging from 4.2% to 56.8%.

Earth-covered peat and earth-covered murshic soils cover 20.6% of the area of organic soils (Table 1) and occur in complexes with strongly silted murshic soils and shallow alluvial soils overlying peat. The largest areas of these soils are found around Nowy Dwór Gdański and Jegłownik (Fig. 1). The surface layer of these soils consists of mineral-organic alluvium. In earth-covered peat soils, muddy soils, and murshic gyttja soils, a high degree of

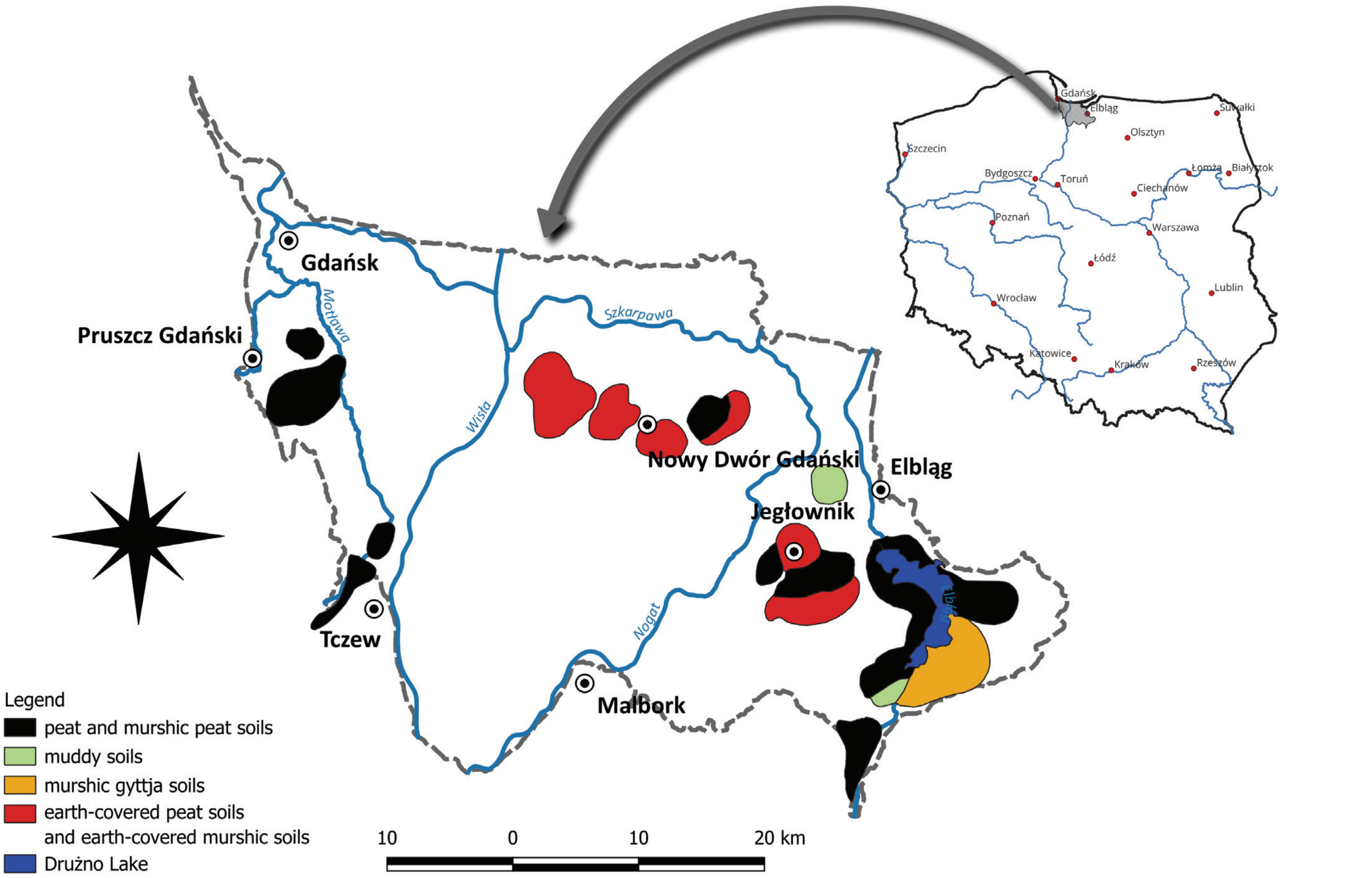

Fig. 1. Location of studied soils in the Vistula Delta region (symbols as in Tables 2 and 3)

Table 2
Basic properties of organic soils in the Vistula Delta

Soil horizon	Depth	Soil formation	pH		Ash	TOC	TN	TOC/TN
	cm		H_2O	KCl	%	g kg^{-1}		
1. Murshic peat soils, hemic (slightly silted), *EZ–ŁIV–d, –0.4 m a.s.l.								
M1	0–10	Peat mursh	6.0	5.0	41.7	340	23.1	14.7
M2	10–25	Peat mursh	6.2	5.5	28.0	447	24.2	18.5
Oe1	25–40	Reed peat	6.4	5.6	24.5	493	23.7	20,8
Oe2	40–75	Reed peat	6.4	5.9	14.2	408	20.6	19.8
Oi	75–210	Reed peat	6.3	5.9	14.9	398	22.3	17.8
2. Murshic peat soils, fibric (strongly silted), EZ–ŁIV–d, –1.2 m a.s.l.								
M	0–22	Peat mursh	6.3	5.9	63.5	152	13.2	12.0
Oa	22–33	Reed peat	6.0	5.6	11.9	472	20.2	23.4
Oi1	33–78	Reed peat	5.5	4.7	4.2	481	21.6	22.3
Oi2	78–180	Reed peat	5.0	4.0	4.6	491	20.7	23.7
3. Sapric murshic soils (strongly silted), E–RIVa, +2.5 m a.s.l.								
M1	0–15	Peat mursh	6.7	6.1	59.3	179	15.7	11.4
M2	15–36	Peat mursh	7.0	6.2	57.3	184	15.9	11.6
Oa	36–53	Alder wood peat	6.7	6.2	56.8	184	15.4	11.9
G	53–150	Silt	6.6	6.1	–	–	–	–
4. Earth–covered peat soils, fibric, EZ–ŁIII–a, 0.0 m a.s.l.								
Ap	0–25	Mineral-organic formation	7.2	6.7	82.0	72.6	6.3	11.5
Oa	25–37	Reed peat	6.2	5.6	31.2	320	18.2	17.6
Oi1	37–60	Reed peat	5.6	5.2	10.5	434	20.0	21.7
Oi2	60–200	Sedge peat	5.7	5.2	10.0	443	21.1	21.0
5. Muddy soils, EZ– ŁIV–f, –0.2 m a.s.l.								
A	0–25	Mineral-organic formation	6.9	6.0	85.5	66.2	5.9	11.3
Ll1	25–31	Mud	7.0	6.2	62.8	184	17.4	10.5
Ll2	31–60	Mud	7.8	7.2	76.9	125	10.1	12.3
G	60–150	Sand	8.0	7.3	–	–	–	–
6. Murshic gyttja soils, EZ–ŁV–x, –1.2 m a.s.l.								
M	0–22	Gyttja mursh	6.1	5.8	73.0	132	13.0	10.2
Lc1	22–30	Gyttja	7.2	6.7	74.1	129	13.8	9.4
Lc2	30–150	Gyttja	7.7	7.2	77.9	124	9.0	13.8

Explanation: TOC – total organic carbon; TN – total nitrogen; *EZ – marsh and post-marsh soils; ŁIV-d; Ł – meadow; R – arable soil, IV – soil class; d – soil variety, (Urzędowa tabela klas gruntów – Official table of land classes, 2012)

siltation of the surface horizons is observed, with mineral matter content ranging from 73.0% to 85.5%. The organic carbon content in the surface horizons of these soils is lower than in peat and murshic soils, ranging from 66.2 g kg^{-1} to 132.2 g kg^{-1}.

Murshic gyttja soils form a large, compact complex around Lake Drużno (Fig. 1) and occupy 2,039.0 ha (Table 1). These soils developed from clay-detritus gyttja, which contains 74.1–77.9% ash. They are characterized by a narrow TOC/TN ratio (9.0–13.8), consistent with the findings of Uggla (1968) in the Masurian Lake District.

Mud soils occupy the smallest area among the organic soils (Table 1) and occur west of Elbląg, in the old riverbeds of the Nogat River (Fig. 1). The ash contents in the muds ranges from 62.8% to 76.9%, and their thickness reaches 60 cm. In the humus horizon, a mineral-organic layer containing 85.5% ash is present.

The reaction of the analysed organic soils ranged from strongly acidic to alkaline (Table 2). In slightly silted murshic soils, pH_{KCl} values increased with depth – from 5.0 in murshic horizon (M1) to 5.9 in the peat horizon. In strongly silted and earth-covered peat soils, pH_{KCl} values ranged from 4.0 to 6.7, and were higher in surface horizons than in the deeper peat layers. The pH of muddy soils (pH_{KCl} 6.0–7.3) was similar to that of murshic gyttja soils (pH_{KCl} 5.8–7.2).

Siltation and mursh formation in the surface horizons of organic soils have significantly influenced their physical and air-water properties. The silted and strongly silted surface horizons of murshic soils were more compacted than the deeper peat horizons. The bulk density of murshic horizons ranged from 0.33 to 0.64 Mg m^{-3}, with total porosity ranging from 73.8% to 81.0%. In contrast, in peat horizons, the bulk density was much lower (0.08–0.41 Mg m^{-3}) and total porosity higher (80.2–94.5%) (Table 3).

High siltation of the surface horizons of murshic soils resulted in a decrease of total porosity and changes in the distribution of pore sizes. In murshic horizons, the volume of macropores was smaller (13.8–16.5%) and the volume of micropores greater (26.0–33.0%) than in peat horizons. The field water capacity (pF 2.0) and available water content (AWC) were lower in murshic horizons compared to peat horizons. The water retention at pF 2.0 in murshic horizons was on average 10 percentage points lower than in peat horizons, ranging from 55.0% to 64.9%, compared with 64.5% to 74.5% in peat horizons (Table 3).

Table 3
Air-water properties of organic soils in the Vistula Delta

Soil horizon	Depth	Sd	Bd	TP	pF 2.0	pF 3.0	pF 4.2	Macro	AWC*	RAWC	SAWC	Macro/ /TP	AWC/ /TP	Micro/ /TP
	cm	Mg m^{-3}		% vol.										
1. Murshic peat soils, hemic (slightly silted)														
M1	0–10	1.910	0.450	76.5	62.1	42.3	27.9	14.4	34.2	19.8	14.4	18.9	44.7	36.5
M2	10–25	1.709	0.326	81.0	64.9	45.0	26.0	16,1	38.9	19.9	19.0	19.9	48.1	32.1
Oe1	25–40	1.721	0.190	88.9	73.9	58.3	30.5	15.0	43.4	15.6	27.8	16.9	48.9	34.3
Oe2	40–75	1.607	0.151	90.6	74.5	55.7	27.2	16.1	47.3	18.8	28.5	17.8	55.2	30.1
Oi	75–210	1.615	0.121	92.5	72.4	54.0	20.0	20.1	52.3	18.4	34.0	21.8	56.6	21.7
2. Murshic peat soils, fibric (strongly silted)														
M	0–22	2.149	0.564	73.8	56.0	45.0	33.0	13,8	27.0	14.0	13.0	18.6	36.5	44.7
Oa	22–33	1.582	0.169	89.3	72.8	55.5	29.0	16.5	43.8	17.3	26.5	16.3	51.3	32.5
Oi1	33–78	1.497	0.083	94.5	72.0	47.4	21.9	22.5	50.1	24.6	25.5	23.8	53.1	23.2
Oi2	78–180	1.480	0.084	94.4	71.7	46.6	23.4	22.7	48.3	25.1	23.2	24.1	51.2	24.8
3. Sapric murshic soils (strongly silted)														
M1	0–15	2.103	0.481	77.1	62.5	43.6	28.4	14.6	34.1	18.9	15.2	19.0	40.8	36.9
M2	15–36	2.088	0.640	69.3	55.0	41.3	29.0	14.3	26.0	13.7	12.3	20.7	37.6	41.9
Oa	36–53	2.076	0.412	80.2	64.5	44.2	26.8	15.7	37.7	20.3	17.4	19.6	47.0	33.5
4. Earth-covered peat soils														
Ap	0–25	2.354	1.012	57.0	50.8	39.5	28.0	6.2	22.8	11.3	11.5	10.9	40.0	49.2
Oa	25–37	1.798	0.258	85.7	71.2	66.7	28.6	14.5	42.6	15.5	27.1	17.0	49.7	33.4
Oi1	37–60	1.567	0.120	92.3	73.0	52.5	19.7	19.3	53.3	20.5	32.8	21.0	57.8	21.4
Oi2	60–200	1.561	0.110	92.9	69.5	38.3	17.6	23.4	51.9	31.2	20.7	25.2	55.9	19.0
5. Muddy soils														
A	0–25	2.392	1.037	56.6	50.0	42.8	31.0	6.60	19.0	7.2	11.8	11.7	33.6	54.8
Ll1	25–31	2.142	0.416	80.6	65.0	46.6	29.2	15.6	35.8	18.4	17.4	19.4	44.5	36.3
Ll2	31–60	2.297	0.377	83.6	63.5	45.5	26.0	20.1	37.5	18.0	19.5	24.1	44.9	31.1
6. Murshic gyttja soils														
M	0–22	2.254	0.711	68.5	62.0	51.5	32.8	6.50	29.2	10.5	18.7	9.50	42.7	47.9
Lc1	22–30	2.266	0.494	78.2	72.8	62.2	37.0	5.40	35.8	10.6	25.2	6.90	45.8	47.4
Lc2	30–150	2.344	0.423	82.0	74.0	60.5	34.5	8.00	39.5	13.5	26.0	9.80	48.2	42.1

Explanation: *AWC – available water capacity; Macro – macropores; Micro – micropores; RAWC – readily available water capacity; SAWC – small pores available water capacity; TP – Total porosity

In the surface horizons of murshic soils, the proportion of micropores in total porosity was higher (32.1–44.7%), while the proportion of mesopores (AWC) was lower (36.5–48.1%) than in peat horizons. Similar values of bulk density, porosity, and water capacity for hydrogenic soils, as well as the influence of siltation on their properties, were reported by Piaścik and Sowiński (Piaścik et al., 1998; Sowiński et al., 2005). Siltation of the surface horizons of murshic soils caused greater compaction, reduced total porosity (including macropores), decreased water retention (pF 2.0), and reduced plant-available water content compared to the deeper peat horizons within the soil profiles.

In earth-covered peat soils and muddy soils, the surface horizons showed the highest degree of compaction, with bulk density values ranging from 1.01 to 1.04 Mg m^{-3} and total porosity from 56.6% to 57.0%. In peat and muddy layers of these soils, total porosity was 24.0–35.9 percentage points higher than in the surface horizons. In the surface horizons of these soils, the air-water and retention properties were unfavorable.

The volume of macropores in the topsoil of earth-covered peats and muddy soils was small (6.2–6.6%), as well as field water capacity (pF 2.0) and available water content (AWC) were lower, compared to deeper soil horizons. The share of unavailable water at pF 4.2 in total porosity was high, ranging from 49.2% to 54.8% (Table 3). The low macropore volume and high micropore volume in the mineral-organic horizons of muddy soils were also reported in studies by Kalisz and Łachacz (2009) and Roj-Rojewski (2003).

In murshic gyttja soils, the degree of compaction in the surface horizons was slightly lower than in earth-covered peat soils and muddy soils. The bulk density was 0.71 Mg m^{-3}, and the total porosity was 68.5%. Within the profile of murshic gyttja soils, the volume of macropores was similar throughout the profile, ranging from 5.4% to 8.0%, while the content of water unavailable to plants varied from 32.8% to 37.0%.

Among the exchangeable cations in the sorption complex of organic soils, calcium dominates, accounting for 24.4–90.4%, followed by hydrogen (6.0–68.5%), and the percentage of magnesium ranges from 2.6% to 11.4% (Table 4). The share of exchangeable sodium (0.1–1.6%) is greater than that of potassium (0.1–0.6%), which is concentrated in the surface horizons (murshic and humus layers). The TEB in murshic horizons of peat and murshic soils ranged from 106 to 121 cmol(+) kg^{-1}, while in the humus horizons of earth-covered and muddy soils and in the M horizon of gyttja soils, it was approximately two times lower (51.4–51.6 cmol(+) kg^{-1}).

Calculated correlation coefficients showed that bulk density (r = 0.864**) and the amount of unavailable water (pF 4.2, r = 0.708**) were significantly positively correlated with the mineral fraction content, and negatively correlated with organic carbon content (Table 5). In contrast, organic carbon content had a significantly positive influence on total porosity (r = 0.817**), including macropore volume (r = 0.688**), field water capacity (r = 0.666*), and available water content (r = 0.817**). The correlation coefficients also indicate significant statistical relationships between the degree of siltation (ash content) and sorption properties. With increasing siltation (loss on ignition), there is a significant positive correlation with the saturation of soils with calcium and potassium cations and with BS, while a negative correlation was observed with the hydrogen cation content in the sorption complex and with CEC (Table 5). The influence of siltation on the exchangeable cation content and cation exchange capacity of peat formations in the Vistula Delta was also confirmed in earlier studies by Smólczyński and Orzechowski (2006). Also, similar relationships in the murshic horizons have been reported for organic soils occurring in valley habitats and intermoraine depressions within the young-glacial landscape of northeastern Poland (Smólczyński and Orzechowski, 2010).

The siltation of organic soils with fine silt-clay material is environmentally beneficial, as the formation of humus-clay complexes (as in muddy soils) after soil drainage protects organic matter from rapid microbial decomposition (Graf-Rosenfeller et al., 2016; Kalisz et. al. 2021). It also has a positive effect on the productive potential of organic soils. According to the official land classification of Poland (Urzędowa…, 2012), the earth-covered soils represent the highest utility value, corresponding to class III permanent grasslands (Ł III). Murshic soils, muddy soils, and even gyttja soils, which are generally considered of low agricultural value (Łachacz et al., 2024), represent class IV grasslands. Meanwhile, murshic soils cultivated arably belong to class IVa arable lands.

The study also demonstrated that most of the variability in the dataset is explained by parameters related to soil water retention, and to a lesser extent by physicochemical properties (Fig. 2). The first principal component (PC1) accounts for 64.12% of the total variance, while the second component (PC2) explains an additional 15.05%, together capturing approximately 79% of the total variability in the dataset. Total organic carbon, macropore volume, readily available water capacity, available water capacity, total porosity, and cation exchange capacity are tightly clustered and oriented in the same direction, reflecting a strong positive interrelationship among these variables. The long vectors of TP, TOC, AWC, RAWC, Bd, and ash indicate their strong influence on the overall data structure. These parameters are closely associated with soil water-holding capacity and capillary rise potential. Variables showing a strong positive correlation with PC1 include total porosity (0.953), available water capacity (0.950), and TOC content (0.928). In contrast, variables strongly negatively correlated with PC1 are bulk density (−0.965), ash content (−0.951), base saturation (−0.718), and water content at pF 4.2 (−0.710). PC2 shows strong correlations with cation exchange capacity (−0.914) and TEB (−0.627). Soil horizons A(5), Ap(4), and M(6) stand apart from the remaining horizons, indicating that they differ significantly in terms of the principal components. Horizons M1(1), Ll1(5), Ll2(5), M1(3), M2(3), and Oa(3) appear to have intermediate values for most of the analyzed parameters, whereas Oi (1), Oi1(2 and 4), Oi2(2 and 4), Oa(2), Oe1(1), and Oe2(1) display distinctly different properties from the rest. The organic (O) horizons, characterized by high positive loadings on PC1, are distinguished by higher TOC content and elevated values of TP, AWC, RAWC, SAWC, and TEB. In contrast, Bd, ash, BS, and pF 4.2 show negative loadings and are typical of the A and M horizons.

Table 4
Sorption properties of organic soils in the Vistula Delta

Soil horizon	Depth	Ca^{+2}	Mg^{+2}	K^{+}	Na^{+}	H^{+}	TEB	CEC	Ca^{+2}	Mg^{+2}	K^{+}	Na^{+}	H^{+}	BS
	cm	cmol(+) kg^{-1}							%					
1. Murshic peat soils, hemic (slightly silted)														
M1	0–12	48.85	3.25	0.29	0.28	56.0	109	52.7	44.9	3.0	0.3	0.3	51.5	48.5
M2	12–25	70.11	2.75	0.10	0.38	48.0	121	73.4	57.8	2.3	0.1	0.3	39.5	60.5
Oe1	25–40	73.56	3.50	0.12	0.52	40.0	118	77.7	62.5	3.0	0.1	0.4	34.0	66.0
Oe2	40–75	70.12	4.63	0.10	0.61	48.0	123	75.5	56.8	3.7	0.1	0.5	38.9	61.1
Oi	75–210	54.60	5.44	0.14	0.62	50.0	111	60.8	49.3	4.9	0.1	0.6	45.1	54.9
2. Murshic peat soils, fibric (strongly silted)														
M	0–22	66.58	9.14	0.38	100	32.0	109	77.1	61.0	8.5	0.3	0.9	29.3	70.7
Oa	22–33	73.52	15.64	0.28	2.13	46.0	138	91.6	53.4	11.4	0.2	1.5	33.4	66.6
Oi1	33–78	40.40	11.19	0.23	1.61	51.0	104	53.4	38.8	10.7	0.2	1.5	48.8	51.2
Oi2	78–180	22.40	4.81	0.23	1.52	63.0	92.0	29.0	24.4	5.2	0.3	1.6	68.5	31.5
3. Sapric murshic soils (strongly silted)														
M1	0–15	82.29	4.60	0.59	0.65	18.0	106	88.13	77.5	4.3	0.6	0.6	17.0	83.0
M2	15–36	87.78	4.81	0.51	0.78	18.0	111	93.88	78.4	4.3	0.5	0.7	16.1	83.9
Oa	36–53	86.03	5.76	0.26	1.30	20.0	113	93.35	75.9	5.2	0.2	1.1	17.6	82.4
4. Earth-covered peat soils, fibric														
Ap	0–25	35.34	4.00	0.27	0.14	12.0	51.8	39.75	68.3	7.7	0.5	0.3	23.2	76.8
Oa	25–37	62.64	6.80	0.14	0.41	49.0	118.9	69.99	52.6	5.7	0.1	0.4	41.2	58.8
Oi1	37–60	41.38	4.95	0.10	0.47	39.0	85.9	46.90	48.2	5.8	0.1	0.5	45.4	54.6
Oi2	60–200	45.69	5.38	0.10	0.57	50.0	101	51.74	44.9	5.9	0.1	0.6	49.1	50.9
5. Muddy soils														
A	0–25	37.00	3.21	015	037	11.0	51.7	40.73	71.5	6.2	0.3	0.7	21.3	78.7
Ll1	25–31	62.35	3.13	0.16	0.87	16.5	83.0	66.51	75.1	3.8	0.2	1.0	19.9	80.1
Ll2	31–60	62.68	2.14	0.09	0.83	6.00	71.7	65.74	87.4	3.0	0.1	1.1	8.4	91.6
6. Murshic gyttja soils														
M	0–22	35.77	3.08	0.26	0.24	12.0	51.4	39.35	69.6	5.8	0.5	0.4	23.3	76.6
Lc1	22–30	75.34	2.38	0.20	0.53	12.0	90.4	78.42	83.3	2.6	0.2	0.6	13.3	85.9
Lc2	30–150	60.00	1.81	0.12	0.47	4.00	66.4	62.40	90.4	2.7	0.2	0.7	6.0	94.0

Explanation: HA – potential (hydrolytic) acidity; TEB – total exchangeable bases; CEC – cation exchange capacity; BS – base saturation;

Table 5
Correlation coefficients between the studied soil properties (* P ≤ 0.01, ** P ≤ 0.05)

Parameters	TOC	TN	Bd	TP	pF 2.0	pF 4.2	Macropores	AWC	RAWC	SAWC
Ash	–0.972**	–0.877**	0.864**	–0.834**	–0.646**	0.708**	–0.746**	–0.841**	–0.761**	–0.631**
TOC	1.000	0.908**	–0.852**	0.817**	0.666**	–0.628**	0.688**	0.817**	0.731**	0.620**
BD	–0.852**	–0.795**	1.000	–0.993**	–0.856**	0.561**	–0.753**	–0.943**	–0.772**	–0.769**

Parameters	Ca^{+2}	Mg^{+2}	K^{+}	Na^{+}	H^{+}	CEC	TEB	Ca^{+2}	Mg^{+2}	K^{+}	Na^{+}	BS
Ash	0.068	–0.505*	0.335	0.197	–0.914**	–0.023	–0.652**	0.813**	–0.274	0.485*	–0.244	0.803**
TOC	–0.053	0.414	–0.325	–0.281	0.897**	0.022	0.651**	–0.768**	0.154	–0.524*	0.186	–0.782**

Explanations as in table 3 and 4

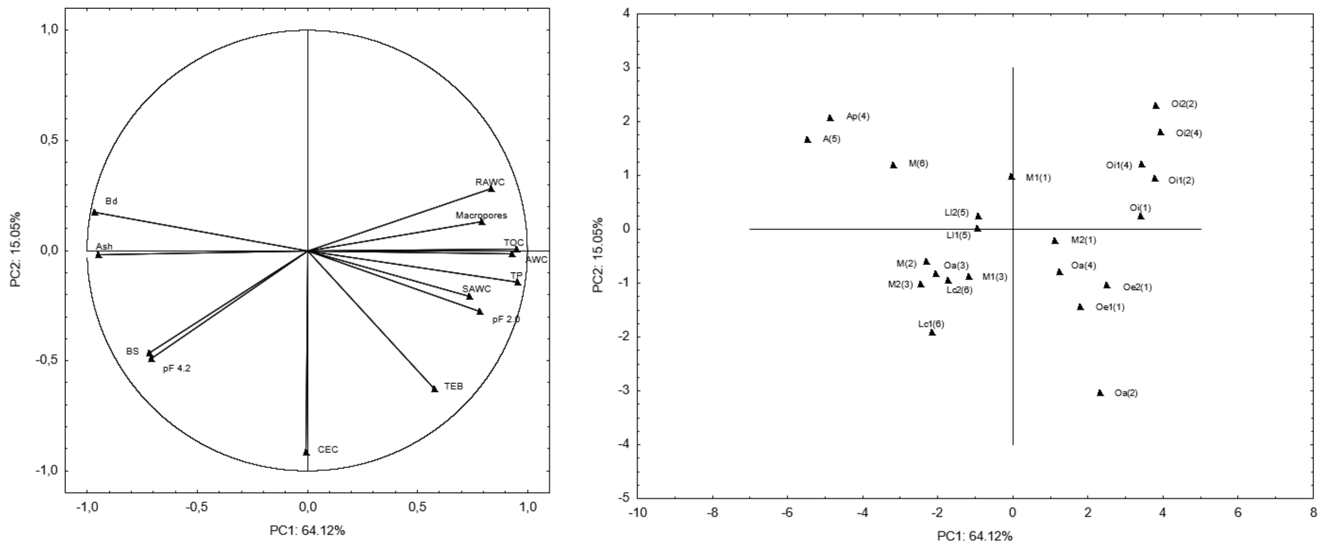

Fig. 2. Relations between studied variables and soil horizons (symbols as in Tables 2–4; in brackets number of the soil profile was provided)

4. Conclusions

- The organic soils of the Vistula Delta are represented by murshic peat soils and murshic soils (slightly and strongly silted), earth-covered peat soils, muddy soils, and murshic gyttja soils. The deposition of alluvial material from river floods played an important role in their formation.
- The degree of silting with fine silt-clay fluvial material significantly affects the development of the air-water, retention, and sorption properties of organic soils. Strong silting determines their specificity and distinguishes them from organic soils in other regions of the country.
- The organic soils of the Vistula Delta are usually a medium-quality grasslands. As a result of heavy silting, they are now frequently used as arable land. Their specific characteristics should be taken into account in both natural and agricultural classification systems.

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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

Barbara Kalisz – Conceptualization, Validation, Data curation, Writing – original draft, Writing – review & editing. **Mirosław Orzechowski** – Conceptualization, Data curation, Investigation, Methodology, Validation, Writing – original draft. **Sławomir Smólczyński** – Conceptualization, Data curation, Investigation, Methodology, Validation, Writing – original draft. **Paweł Sowiński** – Data curation, Methodology, Supervision, Validation, Writing – review & editing. All authors read and approved the final manuscript.

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Geneza, właściwości i klasyfikacja gleb organicznych w Delcie Wisły

Słowa kluczowe

Zamulone gleby organiczne
Mursz
Właściwości retencyjne
Kationy wymienne

Celem niniejszej pracy było przedstawienie genezy i właściwości gleb organicznych występujących na holoceńskiej równinie deltowej najmłodszego w Polsce regionu geograficznego Żuław Wiślanych. Zgodnie z Systematyką Gleb Polski, gleby organiczne reprezentowane były przez: Murshic peat soils, hemic, (slightly silted), (OTmu), Murshic peat soils, fibric, (strongly silted), (OTmu), Sapric murshic soils (strongly silted), (OMsa), Earth-covered peat soils, fibric, (OTnt), (5) Muddy soils, (OJmu), (6) Murshic gyttja soils, (OJmu). Geneza tych gleb ściśle wiąże się z dużą zmiennością warunków wodnych w delcie Wisły, które sprzyjały sedentacji materiałów organicznych: torfów, mułów i gytii oraz zróżnicowaną intensywnością zalewów rzecznych w wyniku których mineralne namuły fluwialne nasycały materiały organiczne w fazie akumulacji i decesji lub osadzały się na ich powierzchni. Zamulenie poziomów powierzchniowych gleb torfowo-murszowych spowodowało większe ich zagęszczenie, zmniejszenie porowatości ogólnej, w tym objętość makroporów, spadek retencji wodnej (pF 2.0) i zawartości wody dostępnej dla roślin w porównaniu do głębiej zalegających w profilach glebowych poziomów torfowych. Ze wzrostem stopnia zamulenia w badanych glebach istotnie dodatnio skorelowany był stopień wysycenia gleb kationami wapnia i potasu, stopień wysycenia gleb kationami zasadowymi (BS), a ujemnie zawartość kationów wodoru w kompleksie sorpcyjnym i pojemność sorpcyjna (TEB). Najwyższą wartość użytkową posiadają gleby natorfowe zaliczane III klasy bonitacyjnej użytków zielonych. Gleby torfowe murszowe, gleby mułowe oraz gleby gytiowe, reprezentują użytki zielone IV klasy bonitacyjnej. Natomiast gleby murszowe użytkowane płużnie zaliczają się do IVa klasy bonitacyjnej gruntów ornych.