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Origin, properties and agricultural value of alluvial soils in the Vistula and Pasłęka deltas, north Poland

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Abstract

The aim of this study was to investigate the sorptive and air-water properties of alluvial soils of the Vistula and Pasłęka deltas, typologically differentiated in terms of habitat conditions, and to determine their agricultural values. Typical ordinary alluvial soils, humic ordinary alluvial soils, and typical brown alluvial soils were developed from loam, sandy loam and silty clay loam and were located in the oldest part of Żuławy, i.e. 'high' Żuławy (from + 2.5 to + 10.0 m a.s.l.). Typical chernozemic alluvial soils and gleyic chernozemic alluvial soils were formed mainly from silt clay, silt loam and clay loam. They were located mainly in the area of 'transitional' Żuławy (from 0.0 to + 2.5 m a.s.l.), 'low' Żuławy (less than 0.0 m a.s.l.) and in the Pasłęka delta. Chernozemic alluvial soils had greater cation exchange capacity, including base cations, than brown and ordinary alluvial soils. The least favorable air-water relationships were found in ordinary alluvial soils. The volume of macropores in arable horizons of these soils ranged from 3.1% to 4.5%. The ratio of macro- to meso- and micropores was wide: 1: 4.0–5.5: 3.6–5.4, while in chernozemic alluvial soils it was 1: 1.8–2.9: 2.5–3.8. The most favorable air-water relationships were found in arable horizons of typical brown alluvial soils, in which the macro- to meso- and micropores ratio was 1.0: 1.9: 0.7. Ordinary and brown alluvial soils were of 'high' Żuławy were properly or periodically excessively moist, and they are mainly classified as good and medium good arable soils, class RIIIa and RIIIb, of the good wheat soil-agricultural complex. The chernozemic alluvial soils of 'depressive' Żuławy were periodically excessively moist, periodically wet, or permanently wet in the depressive parts of the land. These soils are mainly classified as arable soils medium good, class RIIIb and medium value arable soils, classes RIVa and RIVb, of good wheat soil-agricultural complex and strong forage soil-agricultural complex. The alluvial soils particularly rich in fine silt and clay fractions (over 60%) in depressive areas should be used as permanent grasslands. The conducted research has shown that the soil conditions in the delta areas of the Vistula and Pasłęka river mouths are closely related to the origin and land hypsometry, which differentiates the water conditions, the grain size of soil formations, their type and thickness.

1. Introduction

In Poland, the largest area of alluvial soils formed from delta sediments occurs at the mouths of the Vistula and Pasłęka in the Żuławy Wiślane and Staropruska Lowland mesoregions. It represents the delta coastal landscape, which is distinguished by a flat relief, low altitude, high groundwater level and the origin of alluvial soils (Witek, 1965; Kondracki, 2000; Robakiewicz, 2010). This area is a Holocene plain, shaped by the accumulative activity of rivers and man-made technical interventions. Consequently, the Pleistocene formations were covered with Holocene fluvial sediments from which alluvial soils were developed (Piaścik et al., 1991; Hulisz et al., 2015). The origin and formation of the river delta is a complex process and depends on numerous factors: the quantity of sedimented material, the character and topgraphy of the estuary, the direction of sea tides, and others (Wang et al., 2015; Wang et al., 2019). Taking into account the hypsometry of the Vistula delta, two subregions can be distinguished: 'high' Żuławy, located from + 2.5 to + 10.0 m a.s.l. and 'low' Żuławy, located below + 2.5 m a.s.l. Additionally, within 'low' Żuławy, 'transitional' Żuławy, located from 0.0 to + 2.5 m a.s.l. and 'depressive' Żuławy situated below sea level were distinguished (Witek, 1965; Piaścik et al., 2000). Alluvial soils are the soils that show great variability in terms of morphology, physicochemical properties, water retention properties and productivity (Skuodiene et al., 2016; Kercheva et al., 2017; Dezső et al., 2019; Gajić, 2020). They occur in river valleys and delta areas, and show large spatial differentiation (Ligęza, 2016). The drainage works carried out in these areas lowered the groundwater level and enabled agricultural use of these soils, which also contributed to the transformation of their morphology and properties (Laskowski, 1986; Dąbkowska-Naskręt, 1990; Chojnicki, 2002; Ligęza, 2016; Łabaz and Kabała, 2016). The alluvial soils of the Vistula and Pasłęka deltas were formed mainly from fine-fraction fluvial deposits such as clays, silty clays, as well as silts and sandy loams (Klasyfikacja uziarnienia…. PTG 2008). Therefore, in the delta areas of Żuławy Wiślane and Staropruska Lowland, heavy and very heavy alluvial soils prevail, which are difficult to cultivate and they require appropriate agrotechnical and agromeliorative management. Due to the high content of clay, these soils are described by farmers as minute soils due to the fact that their mechanical properties strongly depend on the water content.

The aim of this study was to investigate the sorptive and air-water properties of alluvial soils of the Vistula and Pasłęka deltas, typologically differentiated in terms of habitat conditions, and to determine their agricultural values.

2. Materials and methods

The studies on alluvial soils in the delta of Żuławy Wiślane and the Staropruska Lowland were carried out by the Department of Soil Science (currently the Department of Soil Science and Microbiology) as part of various research projects and works of the departmental program „Improvement of technology and agricultural production in Żuławy". During the studies, over 50 soil profiles of alluvial soils were examined. These studies resulted in numerous scientific monographs and publications (e.g. Piaścik et al., 1998; Piaścik et al., 2000; Orzechowski et al., 2005; Orzechowski and Smólczyński, 2010; Orzechowski et al., 2020). This paper presents the results of the research of 6 selected alluvial soils from the delta areas of the Vistula and Pasłęka estuaries (Table 1), which, in accordance with the newest classification of Polish soils, are: typical ordinary alluvial soils (1), humic ordinary alluvial soils (1), typical brown alluvial soils (1), typical chernozemic alluvial soils (2) and gleyic chernozemic alluvial soils (1) (Kabała et al., 2019). In collected soil samples, the following soil properties, using standard methods for mineral soil studies, were determined: soil texture by Bouyoucos-Casagrande method modified by Prószyński, pH in H_2O and in 1 mol dm^{-3} KCl by the potentiometric method. The content of organic carbon (TOC) and total nitrogen (TN) was analysed using a CN Vario Max Cube Elementar analyser. The content of exchangeable base cations was determined in the extract of ammonium acetate – CH_3COONH_4 (1 mol dm^{-3}) at the pH of 7.0 using iCAP 7400 ICP-OES Thermo Scientific spectrometer. Hydrolytic acidity (HA) was determined by Kappen method after extraction with 1 mol dm^{-3} CH_3COONH_4 (Van Reeuwijk, 2002). The cation exchange capacity (CEC) was calculated as the sum of total exchange bases (TEB) and HA. Specific density (Sd) was determined by pycnometric method and soil bulk density (Bd) was determined in undisturbed 100 cm^3 soil steel cylinders taken at four replications. 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 3.0 and pF 4.2) chambers. Water capacities (Wv/v) were examined at water potential of 98.1 hPa (pF 2.0), 981.0 hPa (pF 3.0) 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 3.0), and small pores available water capacity – SAWC (Wv/v at pF 3.0 – Wv/v at pF 4.2) were calculated (Zawadzki, 1973; Walczak et al., 2002).

Statistical calculations were carried out using Statistica 13.0 software.

3. Results and discussion

Heavy, very heavy and medium alluvial soils formed from silt loam, silt clay and loam prevail in the delta area of the Vistula and Pasłęka estuaries (PTG 2008). The variable sedimentation conditions of fluvial materials influenced the diversification of the texture, TOC content and sorptive properties in the soil pedons. Alluvial soils formed from silts contained 10–26% of clay (<0.002 mm) and over 53% of silt (0.05–0.002 mm) in arable horizons (Ap). The content of clay in arable horizons of soils formed from loam was slightly higher and ranged from 13% to 27%, while the content of silt was lower, and ranged from 40% to 45% (Table 1). These soils were qualified as typical ordinary alluvial soils and typical brown alluvial soils. They are located mainly in the oldest part of the delta ('high' Żuławy) and they situated at an altitude of + 2.5 m to + 10.0 m a.s.l. (Piaścik et al., 2000). In delta areas below + 2.5 m a.s.l. ('low' Żuławy) typical chernozemic alluvial soils and gleyic chernozemic alluvial soils prevailed. Gleyic chernozemic alluvial soils occurred mainly in the depressive areas of the Vistula and Pasłęka deltas. These soils often qualify as shallow and medium-deep alluvial soils on hemic or sapric peat, drained with open ditches and pump stations (Piaścik et al., 1991). Due to the high content of clay, low location in a relief and high level of groundwater, gleyic and sod-forming processes have a dominant impact on the formation, evolution and properties of alluvial soils darniowe (Witek, 1965; Kowalik, 1968; Niedźwiecki, 1971; Kholodov, 2010; Dezső et al., 2019; Kawałko et al., 2021).

3.1. Sorptive, physical and air-water properties

The content of organic carbon in humus horizons of the studied alluvial soils ranged from 8.1 g kg^{-1} to 21.4 g kg^{-1}. The thickness of humus horizons in typical ordinary alluvial soils and typical brown alluvial soils reached 30 cm, while in typical chernozemic alluvial soils and gleyic chernozemic alluvial soils it ranged from 45 cm to 68 cm (Table 1). The ratio of TOC/TN was narrow and ranged from 8.0 to 11.4, which proves that the humification processes are highly advanced. The soil reaction of studied arable horizons ranged from slightly acidic (KCl pH 5.6) to neutral (KCl pH 6.9).

Table 1
Selected basic properties of studied alluvial soils

Ho-rizon	Depth cm	Soil texture PTG 2008, USDA	Percentage of fraction in diameter (mm)						pH		TOC	Organic matter	TN	TOC: TN
			> 2.0	2.0– –0.05	0.05– –0.02	0.02– –0.002	0.05– –0.002	< 0.002	H_2O	KCl	g kg^{-1}			
1. Typical ordinary alluvial soils (SGP 2019), Eutric Fluvisols (Ochric), (WRB 2015), (Parszewo, Żuławy Wiślane), RIIIa-c*, 2Fs**, + 3.0 m a.s.l														
Ap	0–28	Glina zwykła, loam	0	29	22	22	44	27	7.6	6.8	15.2	26.2	1.45	10.5
C1	28–70	Glina piaszczysta, sandy loam	0	74	13	4	17	9	8.0	7.3				
C2	70–110	Glina zwykła, loam	0	45	26	13	39	16	7.9	7.0				
Cgg	110–150	Glina pylasto-ilasta, silty clay loam	0	11	9	49	58	31	7.7	6.9				
2. Humic ordinary alluvial soils (SGP 2019), Eutric Fluvisols (Humic), (WRB 2015), (Lichnowo, Żuławy Wiślane), RIIIa-c, 2Fs, + 5.0 m a.s.l														
Ap	0–30	Glina zwykła, loam	0	43	21	23	44	13	7.1	6.2	16.2	28.0	1.64	9.9
A2	30–45	Glina zwykła, loam	0	40	20	21	41	18	7.0	6.1	10.1	17.3	1.18	8.5
C1	45–84	Glina piaszczysta, sandy loam	0	66	16	8	24	10	7.4	6.6				
C2	84–120	Glina lekka, sandy loam	0	56	19	10	29	15	7.4	6.7				
Cgg	120–150	Ił pylasty, silty clay	0	9	12	30	42	49	7.3	6.3				
3. Typical brown alluvial soils (SGP 2019), Fluvic Cambisols (Ochric), (WRB 2015), (Drewnica, Żuławy Wiślane), RII-c, 1Fs, + 5.5 m a.s.l														
Ap	0–28	Glina zwykła, loam	0	41	28	12	40	19	7.6	6.8	13.4	23.1	1.18	11.4
Bw	28–65	Glina zwykła, loam	0	34	35	13	48	18	7.7	6.9				
C	65–150	Glina zwykła, loam	0	33	34	15	49	18	7.6	6.9				
4. Typical chernozemic alluvial soils (SGP 2019), Fluvic Phaeozems, (WRB 2015), (Marynowy, Żuławy Wiślane), RIIIb-f, 2Fc, + 0.5 m a.s.l														
Ap	0–32	Pył ilasty, silt loam	0	27	20	33	53	20	6.4	5.8	20.3	35.0	1.99	10.2
A2	32–45	Glina ilasta, clay loam	0	22	19	31	50	28	6.4	5.7	19.5	33.6	1.69	11.5
C	45–90	Ił pylasty, silty clay	0	9	10	36	46	45	6.7	5.8				
Cgg	90–150	Glina pylasto-ilasta, silty clay loam	0	19	18	28	46	35	6.9	6.0				
5. Typical chernozemic alluvial soils (SGP 2019), Fluvic Phaeozems, (WRB 2015), (Braniewo, Wybrzeże Staropruskie), RIIIb-g, 2Fs, + 0.3 m a.s.l														
Ap	0–32	Pył gliniasty, silt loam	0	38	25	28	53	10	6.1	5.6	18.6	32.1	1.94	9.6
A2	32–45	Pył gliniasty, silt loam	0	38	26	26	52	10	5.9	5.3	8.1	14.0	0.98	8.3
A3	45–68	Pył ilasty, silt loam	0	17	12	46	58	25	6.0	5.4	19.6	33.8	2.15	9.1
Oe	68–85	Torf niski hemowy, peat							5.6	4.9		652.0		
Cgg	85–150	Glina pylasto-ilasta, silty clay loam	0	19	11	42	53	28	5.9	5.3				
6. Gleyic chernozemic alluvial soils (SGP 2019), Fluvic Gleyic Phaeozems, (WRB 2015), (Marzęcino, Żuławy Wiślane), RIVa-d, 8Fc, – 1.0 m a.s.l														
Ap	0–32	Pył ilasty, silt loam	0	15	23	36	59	26	7.6	6.9	21.4	36.9	2.68	8.0
A2	32–55	Pył ilasty, silt loam	0	14	19	41	60	26	7.5	6.7	9.4	16.2	1.16	8.1
C2gg	55–150	Pył ilasty, silt loam	0	9	16	51	67	24	7.7	6.9				

Explanation: TOC – total organic carbon; TN – total nitrogen; *RIIIa-c; R – arable soil, IIIa – soil class, c – soil variety (Official table of land classes) **2Fs; 2 – agriculural land suitability, Fs – medium alluvial soil, Fc – heavy alluvial soil

Chernozemic alluvial soils were distinguished by higher total exchangeable bases (TEB) in humus horizons as compared to the ordinary and brown alluvial soils. The total exchangeable bases in these soils ranged from 20.56 cmol(+) kg^{-1} to 48.37 cmol(+) kg^{-1} (Table 2). The content of cations in the pedons of the studied alluvial soils was varied and depended on the content of humus and clay. The greatest CEC, including the content of base cations, was found in gleyic chernozemic alluvial soils located at the 'depressive' Żuławy. These soils contained more than 40.16 cmol(+) kg^{-1} of base cations (Ca^{2+}, Mg^{2+}, K^+ and Na^+) and were developed from silt loam with higher amount of clay fraction. Alluvial soils formed from silt clay had high CEC, while

Table 2
Sorptive and air-water properties of studied alluvial soils

Hori-zon	Depth cm	Soil texture PTG	Specific density Mg m^{-3}	Bulk density	Total porosity	pF			Macro-pores	AWC	RAWC	SAWC	TEB cmol(+) kg	CEC	HA	BS %
						2.0	3.0	4.2								
					% vol.											
1. Typical ordinary alluvial soils																
Ap	0–28	gz	2.633	1.660	37.0	33.9	27.5	16.8	3.1	17.1	6.4	10.7	22.52	21.47	1.05	95.4
C1	28–70	gp	2.690	1.597	40.6	32.8	21.2	9.2	7.8	23.6	11.6	12.0	10.35	9.55	0.80	92.3
C2	70–110	gz	2.688	1.604	40.3	33.1	24.6	14.8	7.2	18.3	8.5	9.8	13.93	13.18	0.75	94.7
Cgg	110–150	gpyi	2.531	1.315	48.0	42.6	33.5	21.0	5.4	21.6	9.1	12.5	24.83	23.03	1.80	92.8
2. Humic ordinary alluvial soils																
Ap	0–30	gz	2.525	1.581	37.4	32.9	26.2	15.1	4.5	17.8	6.7	11.1	18.83	16.28	2.55	86.4
A2	30–45	gz	2.611	1.593	39.0	33.8	27.6	16.3	5.2	17.5	6.2	11.3	19.64	17.74	1.90	90.3
C1	45–84	gp	2.653	1.566	41.0	32.7	22.4	11.6	8.3	21.1	10.3	10.8	11.61	10.81	0.80	93.1
C2	84–120	gl	2.618	1.594	39.1	30.4	19.8	12.3	8.7	18.1	10.6	7.5	9.41	8.66	0.75	92.0
Cgg	120–150	ipy	2.540	1.284	49.4	44.6	38.0	27.1	4.8	17.5	6.6	10.9	36.38	34.98	1.40	96.1
3. Typical brown alluvial soils																
Ap	0–28	gz	2.584	1.506	41.7	30.5	17.0	9.5	11.2	21.0	13.5	7.5	15.75	14.97	0.75	95.0
Bw	28–65	gz	2.646	1.430	46.0	33.0	17.0	9.5	10.0	23.5	16.0	7.5	19.85	19.10	0.75	96.2
C	65–150	gz	2.660	1.383	48.0	38.0	19.5	11.0	8.0	27.0	18.5	8.5	17.28	16.68	0.60	96.5
4. Typical chernozemic alluvial soils																
Ap	0–32	pyi	2.551	1.312	48.6	40.5	31.0	21.8	8.1	18.7	9.5	9.2	26.28	21.63	4.65	82.3
A2	32–45	gi	2.612	1.517	41.9	35.2	26.1	18.2	6.7	17.0	9.1	7.9	28.32	24.12	4.20	85.2
C	45–90	ipy	2.593	1.287	50.4	45.7	39.5	29.4	4.7	16.3	6.2	10.1	39.21	35.96	3.25	91.7
Cgg	90–150	gpyi	2.620	1.344	48.7	43.2	34.6	24.1	5.5	19.1	8.6	10.5	30.41	27.71	2.70	91.1
5. Typical chernozemic alluvial soils																
Ap	0–32	pyg	2.538	1.376	45.8	37.1	29.5	21.8	8.7	15.3	7.6	7.7	31.12	24.07	7.05	77.4
A2	32–45	pyg	2.589	1.533	40.8	34.2	27.1	19.3	6.6	14.9	7.1	7.8	20.56	14.48	6.08	70.5
A3	45–68	pyi	2.476	1.127	54.5	51.1	42.0	32.2	3.5	18.8	9.1	9.7	37.24	29.33	7.94	78.8
Oe	68–85	torf	2.120	0.502	76.3	64.2	44.5	28.8	12.1	35.4	19.7	15.7	79.12	59.92	19.20	75.8
Cgg	85–150	gpyi	2.351	1.105	53.0	50.2	41.4	31.6	2.8	18.6	8.8	9.8	43.58	33.43	10.15	76.8
6. Gleyic chernozemic alluvial soils																
Ap	0–32	pyi	2.619	1.230	53.0	46.2	37.0	26.5	6.8	19.7	9.2	10.5	48.37	47.32	1.05	97.9
A2	32–55	pyi	2.632	1.201	54.4	48.1	40.5	27.7	6.3	20.4	7.6	12.8	40.91	40.16	0,75	98.2
C2gg	55–150	pyi	2.694	1.107	58.9	53.0	45.8	33.9	5.9	19.1	7.2	11.9	42.25	41.31	0,94	97.8

Explanation: HA – potential (hydrolytic) acidity; TEB – total exchangeable bases; CEC – cation exchange capacity; BS – base saturation; AWC – available water capacity; RAWC – readily available water capacity; SAWC – small pores available water capacity

the soils formed from sandy loams had the lowest TEB, in the range of 9.41–11.61 cmol (+) kg^{-1}. A similarly high content of exchangeable cations in alluvial soils of the Lower Vistula Valley was found by Dąbrowska-Naskręt (1990), and a slightly lower content in alluvial soils of the Puławy section of the Vistula was reported by Ligęza (2016). The cation exchange capacity, including the content of base cations, was significantly positively correlated with the amount of clay (<0.002 mm, r = 0.625, r = 0.662, respectively) and fine silt (0.02–0.002 mm, r = 0.840, r = 0.788), while a significantly negative correlation was found in relation to sand (2.0–0.05 mm, r = –0.836, r = –0.838), (Table 3). The base saturation (BS) was high and ranged from 82.3% to 98.2% in alluvial soils of Żuławy, whereas in chernozemic alluvial soils of the Pasłęka delta the BS values were slightly lower and ranged from 70.5% to 78.8%.

Alluvial soils in the deltas of the Vistula and Pasłęka estuaries are the most fertile soils in Poland. One of the factors that adversely affects their fertility are unfavorable air-water relations (Witek, 1965; Brandyk, 1988; Orzechowski and Smólczyński, 1998, Piaścik et al., 1998). In studied alluvial soils, the bulk density, which is an indicator of soil compaction, reached higher values in arable horizons of ordinary and brown alluvial soils and ranged from 1.506 Mg m^{-3} to 1.660 Mg m^{-3} and lower values in chernozemic alluvial soils (Table 2). The most favorable air-water relations in arable horizons were found in typical brown alluvial soils. In these soils, the macropores volume amounted to 11.2%, and the water content available for plants (AWC) amounted to 21.0%, encompassing 13.5% of water readily available for plants (RAWC) (Table 2). The ratio of macro- to meso- and micropores was proper (1.0: 1.9: 0.7). The least favorable air-water relations were in ordinary alluvial soils. The macropore volume in arable horizons of these soils ranged from 3.1% to 4.5% and was lower than the critical air pores content for arable lands (10–13%) (Domżał, 1977; Jarvis and Macney, 1979.). The volume of AWC in these horizons ranged from 17.1% to 17.8%, with predominance of SAWC, which content ranged from 10.7% to 11.1% and was close to the volume of water unavailable to plants (pF 4.2). Similar relations were confirmed by the research of Brandyk (1988) and Piaścik et al. (1998). Due to the small volume of air pores, the macro- to meso- and micropores ratio was wide (1: 4.0–5.5: 3.6–5.4). In chernozemic alluvial soils, the volume of water available to plants in arable horizons ranged from 15.3% to 19.7%, with similar volumes of RAWC and SAWC. These soils were characterized by the highest proportion of water unavailable to plants, and the ratio of macro- to meso- and micropores was as follows: 1: 1.8–2.9: 2.5–3.8. Similar values of water retention at the range of pF 2.0–pF 3.0, were found by Laskowski (1986) in very heavy gleyic alluvial soils of the middle Odra valley. In the studied alluvial soils, the values of field water capacity (pF 2.0), pF 3.0, pF 4.2 and total porosity were significantly positively correlated with the content of silt and clay, and significantly negatively correlated with the amount of sand (Table 3).

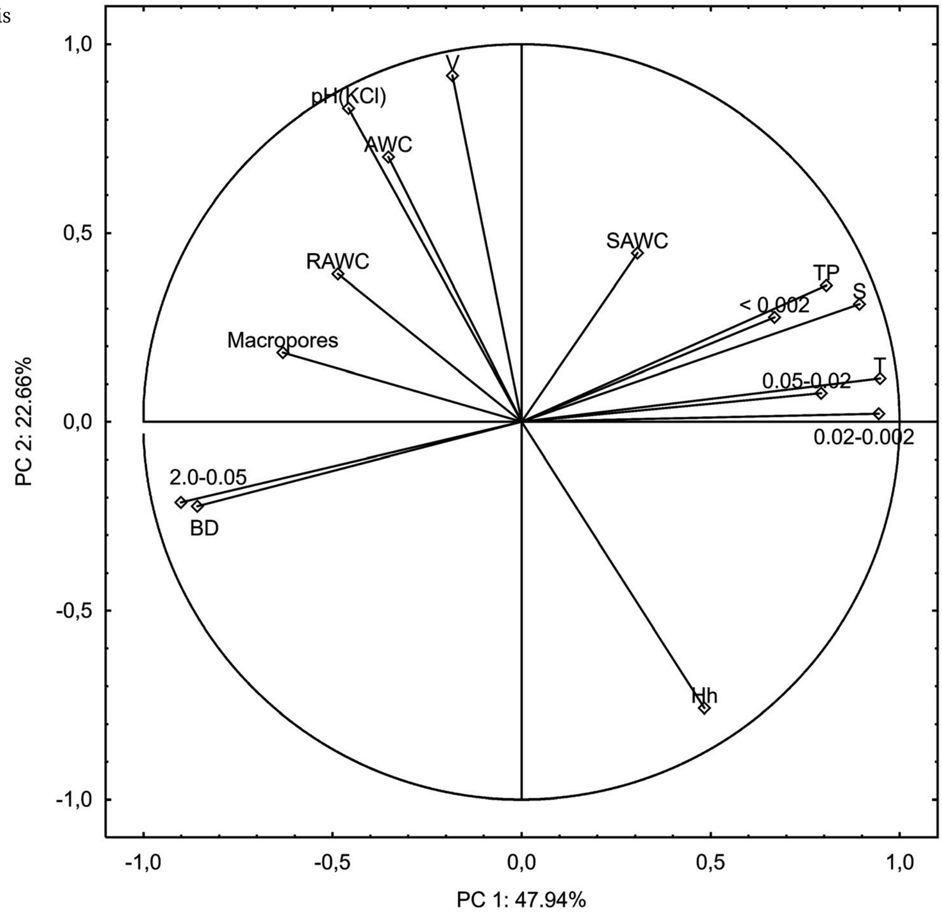
The studied soils had different soil physical and chemical properties which is related to the processes occurring in soils and results in their agricultural value. Usually, the soil agricultural value is more equated with chemical properties. However, there are interrelations between physical and chemical properties and the results of PCA (Fig. 1) confirmed that the variability of the soils may be more dependent of the physical properties. The PC 1 explained 47.94% of the variability of the data and PC 2, 22.66%. Soil physical properties had greater effect on the development of soil and soil agricultural value. PC 1 was significantly correlated mainly with soil physical properties: fraction with diameter of 2.0–0.05 mm (–0.900), 0.05–0.002 mm (0.792), 0.02–0.002 mm (0.944), BD (–0.858), and to a lesser extent with soil chemical properties: CEC (0.894) and TEB (0.948). The PC 2

Table 3
Coefficients of correlation between granulometric fractions water-air properties and sorptive properties

Variable	mean	SD	2.0–0.05	0.05–0.002	0.02–0.002	<0.002
2.0–0.05	30.6	18.22	1.000	–0.833*	–0.859*	–0.792*
0.05–0.002	46.8	11.80	–0.833*	1.000	0.842	0.323
0.02–0.002	27.0	13.52	–0.859*	0.842	1.000	0.542*
< 0.002	22.6	10.59	–0.792*	0.323	0.542*	1.000
TEB	26.3	11.64	–0.836*	0.733*	0.840*	0.625*
CEC	23.6	10.88	–0.838*	0.701	0.788*	0.662*
HA	2.7	2.71	–0.227	0.336	0.441*	0.024
BS	89.8	7.90	–0.059	–0.145	–0.194	0.255
Porosity	45,9	6,26	–0,733*	0,697*	0,767*	0,490*
pF 2.0	39,3	7,19	–0,789*	0,686*	0,872*	0,594*
pH 3.0	29,9	8,63	–0,758*	0,627*	0,890*	0,607*
pF 4.2	20,0	7,89	–0,787*	0,675*	0,896*	0,605*
AWC	19,2	2,82	0,193	–0,141	–0,284	–0,177
RAWC	9,3	3,11	0,283	–0,154	–0,453*	–0,311
SAWC	9,9	1,70	–0,199	0,049	0,360	0,278
Macro-pores	6,5	2,16	0,491*	–0,293	–0,583*	–0,511*

* – significance level at α=0.05, SD – standard deviation

Fig. 1. The results of principal component analysis



was in turn strongly correlated with BS (0.916), KCl pH (0.830), HA (–0.757) and to a lesser extent with AWC (0.701).

3.2. Agricultural value

The delta alluvial soils of the Vistula and Pasłęka estuaries are distinguished by their natural fertility and high agricultural value (Witek, 1965; Piaścik et al., 2000; Orzechowski et al., 2004; Orzechowski et al., 2020). Alluvial soils of 'high' Żuławy qualify as properly moist and periodically excessively moist soils, and are underlain by mainly mineral deposits. Periodically excessive water content results from the high compactness of the soil formations and poor water permeability. Such a state of moisture should be considered optimal. These alluvial soils are classified as good and medium-good arable land, class RIIIa and RIIIb, of good wheat soil-agricultural complex (profiles 1, 2; F-RIIIa-c, 2Fs), (Official table of land classes, 2013), and less often as average quality arable land, class RIVa (Table 1). Also, vast areas of 'high' Żuławy are covered with alluvial soils, which are classified as very good arable land, RII class, of a very good wheat soil-agricultural complex (profiles 3; F-RII-b, 1Fs). These alluvial soils have an angular or subangular structure, a plump arrangement and more favorable structure in arable horizons than in the horizons below (Orzechowski and Smólczyński, 2010). The groundwater level lies below the soil profile.

Alluvial soils of 'low' Żuławy were classified as periodically excessively moist, periodically wet, and permanently wet in depressive areas. The depth of the groundwater level depended on the retention capacity of the subsoil. With high water retention of the substrate (peat), the level of groundwater was below 60 cm, and gleyic processes occurred blow 40 cm (zonal gleying or whole horizons were under gleying). These alluvial soils are classified as moderately good arable land, class RIIIb and arable land of average quality, classes RIVa and RIVb, less often arable land class RIIIa. Heavy, deep, humic alluvial soils with gleyic spots at a depth of 50–70 cm (profile 4) were classified as F-RIIIb-f, of good wheat soil-agricultural complex (2Fc). Similarly, typical chernozemic alluvial soils (profile 5) located in the Pasłęka delta were classified as the F-RIIIb-g and of good wheat soil-agricultural complex. It was medium textured alluvial soil, which was formed on low-moor peat at a depth of 68 cm. Whereas, gleyic chernozemic alluvial soils (profile 6), due to the strong gleying that occurs directly below the humus horizons, at a depth of less than 55 cm, should be classified as arable land of average quality, class F-RIVa-d, of strong forage soil-agricultural complex (8Fc). Alluvial soils, particularly rich (over 60%) in fine silt and clay (diameter of less than 0.02 mm) in depressive areas, should be used as permanent grasslands (Piaścik et al., 1991). The conducted research has shown that the soil conditions in the delta areas of the Vistula and Pasłęka estuaries are closely related to the origin and land hypsometry, which differentiate the water conditions, texture of the soil formations, their type and thickness. Also significant was the water retention of the subsoil.

4. Conclusions

In the delta areas of the Vistula and Pasłęka, typical ordinary alluvial soils, humic ordinary alluvial soils and typical brown alluvial soils occur. They were formed from loam, sandy loam and silty clay loam and were located in the oldest part of the delta, 'high' Żuławy (from + 2.5 to + 10.0 m a.s.l.). Typical chernozemic alluvial soils and gleyic chernozemic alluvial soils were formed mainly from silt clay, silt loam and clay loam, and were located mainly in the area of 'transitional' Żuławy (from 0.0 to + 2.5 m a.s.l.), 'depressive' Żuławy (less than 0.0 m a.s.l.) and in the Pasłęka delta. Chernozemic alluvial soils had greater cation exchange capacity, including base cations, than brown or ordinary alluvial soils. The least favorable air-water relationships were found in ordinary alluvial soils. The volume of macropores in arable horizons of these soils ranged from 3.1% to 4.5% and was lower than the critical air pores content for arable land. The ratio of macro- to meso- and micropores was wide: 1: 4.0–5.5: 3.6–5.4, while in chernozemic alluvial soils the volume of macropores was greater than in ordinary alluvial soils, i.e. 6.8–8.7%. These soils had the highest content of water unavailable to plants, and the ratio of macro- to meso- and micropores amounted to 1: 1.8–2.9: 2.5–3.8. The most favorable air-water relationships were found in arable horizons of typical brown alluvial soils, in which the volume of macropores was 11.2% and the macro- to meso- and micropores ratio was 1.0: 1.9: 0.7.

The alluvial soils of the Vistula and Pasłęka estuaries are distinguished by their natural fertility and high agricultural value. Ordinary and brown alluvial soils of 'high' Żuławy qualify for properly moist and periodically excessively moist soils, underlain by mainly mineral deposits. The chernozemic alluvial soils of 'depressive' Żuławy were periodically excessively moist, periodically wet, or permanently wet in the depressive parts of the land. These soils are mainly classified as arable soils medium good, class RIIIb and arable soils of average quality, classes RIVa and RIVb, good wheat soil-agricultural complex and strong forage soil-agricultural complex (8F). The alluvial soils particularly rich in fine silt and clay fractions (over 60%) in depressive areas should be used as permanent grasslands. Ordinary and brown alluvial soils of 'high' Żuławy were mainly classified as good and medium good arable soils, class RIIIa and RIIIb, of good wheat soil-agricultural complex, less frequently as RII and arable land of average quality, class RIVa. The conducted research has shown that the soil conditions in the delta areas of the Vistula and Pasłęka are closely related to the origin and land hypsometry, which differentiate the water conditions, the grain size of the formations, their type and thickness.

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Geneza, właściwości i wartość rolnicza mad delty Wisły i Pasłęki

Słowa kluczowe

Geneza gleb
Mady
Właściwości powietrzno-wodne
Delta Wisły i Pasłęki
Przydatność rolnicza

Streszczenie

Celem pracy było zbadanie właściwości sorpcyjnych i powietrzno-wodnych gleb aluwialnych delty Wisły i Pasłęki, zróżnicowanych typologicznie i pod względem warunków siedliskowych oraz określenie ich wartości rolniczej. Mady właściwe typowe, mady właściwe próchniczne i mady brunatne typowe wytworzyły się z gliny zwykłej, gliny piaszczystej oraz gliny pylasto–ilastej i położone były na terenie najstarszych Żuław wysokich (od + 2.5 do + 10.0 m n.p.m.). Mady czarnoziemne typowe i mady czarnoziemne gruntowo–glejowe wytworzyły się głównie z pyłu ilastego, pyłu gliniastego oraz gliny ilastej. Występowały głównie na ternie Żuław przejściowych (od 0.0 do + 2.5 m n.p.m., Żuław depresyjnych (poniżej 0.0 m n.p.m.) oraz w delcie Pasłęki. Mady czarnoziemne charakteryzowały się większą pojemnością sorpcyjną, w tym zawartością kationów zasadowych niż mady właściwe i brunatne. Najmniej korzystne stosunki powietrzno-wodne stwierdzono w madach właściwych. Objętość makroporów w poziomach ornych tych gleb wahała się od 3.1–4.5%. Stosunek macro- do mezo- i microporów był szeroki i kształtował się jak: 1 : 4.0–5.5 : 3.6–5.4, natomiast w madach czarnoziemnych wynosił on jak: 1 : 1.8–2.9 : 2.5–3.8. Najkorzystniej stosunki powietrzno-wodne w poziomach płużnych kształtowały się w madach brunatnych typowych, w których stosunek macro- do mezo- i microporów kształtował się jak: 1.0 : 1.9 : 0.7. Mady właściwe i brunatne Żuław wysokich były właściwie uwilgotnione oraz okresowo nadmiernie uwilgotnione. Zaliczały się one głównie do gruntów ornych dobrych i średnio dobrych klasy RIIIa i RIIIb, kompleksu pszennego dobrego. Mady czarnoziemne Żuław niskich były okresowo nadmiernie uwilgotnione oraz okresowo podmokłe, a na terenach depresyjnych trwale podmokłe. Mady te klasyfikowały się głównie do gruntów ornych średnio dobrych klasy RIIIb oraz gruntów ornych średniej jakości lepszych i gorszych klas RIVa i RIVb, kompleksu pszennego dobrego oraz kompleksu pastewnego mocnego. Mady szczególnie zasobne we frakcje pyłu drobnego i iłu (powyżej 60%) na terenach depresyjnych powinny być użytkowane jako trwałe użytki zielone. Przeprowadzone badania wykazały, że warunki glebowe na terenach deltowych ujścia Wisły i Pasłęki związane są ściśle z genezą i hipsometrią terenu, która różnicuje stosunki wodne, uziarnienie utworów, ich rodzaj i miąższość.