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Chemical weathering of the middle Vistula and Żuławy (Vistula delta) alluvial soils

Józef Chojnicki*

Warsaw University of Life Sciences – SGGW, Department of Soil Science, Nowoursynowska 159 Str., 02-776 Warszawa, Poland

* prof. dr hab. J. Chojnicki, jozef_chojnicki@sggw.edu.pl, ORCID iD: https://orcid.org/0000-0001-7719-4331

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Abstract

The aim of the study was to investigate the intensity of chemical weathering in arable alluvial, currently unflooded soils of the middle Vistula valley from Puławy to Płock (5 profiles) and in the area of Żuławy (3 profiles). According to the IUSS systematics (IUSS Working Group WRB, 2022), the soils were classified as Eutric Fluvisols, Eutric Gleyic Fluvic Cambisol, Gleyic Fluvic Phaeozems and Gleyic Fluvisols. The soils of the middle Vistula showed respectively mainly light loam texture and clayey silt from Żuławy area. The total content of aluminum, calcium, magnesium, potassium and sodium was determined by X-ray fluorescence (XRF) in soil samples (particles <2 mm in diameter), while basic soil analyses were performed with methods commonly used in soil science. The averages and ranges of the chemical weathering indices values in the Vistula valley and Żuław alluvial soil profiles were Chemical Index of Alteration (CIA) – 64.7 (56.1–80), Harnois's Chemical Index of Weathering (CIW) – 75.7 (67.3–90.5), Plagioclase Index of Alteration (PIA) – 57.9 (44–77.4), Weathering Index of Parker (WIP) – 25.8 (8.8–36.7) and Vogt's Residual Index (V) – 2.3 (1.8–3.1). The indices reached slightly higher values in the soils of Żuławy than in the middle of the Vistula. The tested soils showed slight weathering determined by the values from 60 to 70 of the most commonly used CIA index. However, the average value of this index in the soils of the middle Vistula slightly exceeded the lower value of this range, while in the soils of Żuławy it was close to the upper value. The gley soil-forming process caused by groundwater, taking place in most soils, increased the intensity of chemical weathering in the horizon of iron compounds accumulation. Meanwhile, the humus accumulation, poorly advanced cambisol development and leaching soil-forming processes did not increase the values of chemical weathering indices. The weathering indices showed a slight weathering variation of the examined soils in the cross-section of their profiles and along the Vistula valley, despite the diversity of climatic conditions during the Holocene period and the geological structure of the middle Vistula and Żuławy catchments.

1. Introduction

Alluvial soils are young Holocene soils, formed in specific hydrological, geomorphological and ecological conditions of river valleys, conditioned by the nature of the river, its section, the features of its catchment area, climate and increasing human activity (Dengiz, 2010; Hulisz et al., 2015; Kacprzak et al., 2012; Łabaz and Kabala, 2016; Łachacz and Nitkiewicz, 2021). The geological structure of the catchment area together with the properties of the soils and susceptibility to erosion determine the degree of chemical weathering, properties and the amount of eroded substrate supplied to the river valley (Batista et al., 2017; Kidane et al., 2019). The next steps in the chemical weathering of the substrate take place during its transport (Li and Yang, 2010; Nadłonek and Bojakowska, 2018; Shao et al., 2012) and then in accumulated alluvial sediments. The soil-forming processes enter these weathered alluvial sediments between successive floods in short periods of time, and after embankment of rivers their course is continuous, which causes their further chemical, physical and biological weathering (Dąbkowska-Naskręt, 1990; Jonczak, 2015; Kobierski and Banach-Szott, 2022; Laskowski, 1986; Ligęza, 2016).

The soil-forming processes in the alluvial soils of the middle Vistula and Żuławy show initial stages of development, except for the frequently occurring and intensively ongoing gley soil-forming process caused by groundwater (Chojnicki, 2002; Chojnicki, 2004). Only in the second half of the 19th century (Piskozub, 1982; Witek, 1965) did the construction of flood embankments along the majority of the Vistula river complete the process of alluvial deposition and, at the same time, initiated the continuous occurrence of soil-forming processes. Since then, intensive agricultural use of these fertile soils also began (Czarnowska et al., 1995; Olszewski et al., 1966; Orzechowski et al., 2005), which causes, among others, the intensification of the chemical weathering process and the transformation of clay minerals (Chojnicki, 2001; Chojnicki, 2002).

The aim of the research was to determine the intensity of chemical weathering in cultivated alluvial, currently unflooded soils in the middle Vistula (5 profiles from Puławy to Płock) and in the Żuławy area (3 profiles), taking into account their weathering (1) in profile sections, (2) along the Vistula River and (3) under the influence of soil-formation processes.

2. Materials and methods

The investigations comprised 8 profiles of alluvial soils under tillage, situated outside the embankments of the central Vistula valley (5 profiles) and Żuławy area (3 profiles) at a distance from industrial centres (Fig. 1). The soils were classified using the Polish Soil Classification (2019) as Typical proper alluvial soils (2 profiles), Gleyed brown alluvial soils (4 profiles), Gleyed chernozemic alluvial soil (1 profile), Gley alluvial soil (1 profile) and according IUSS systematics (Working Group WRB, 2022): Eutric Fluvisols, Eutric Gleyic Fluvic Cambisol, Gleyic Fluvic Phaeozems, Gleyic Fluvisols, respectively. Together 32 soil samples (particles <2 mm diameter) were analysed. Field work were developed using methods commonly applied in soil science. In laboratories the total content of aluminum, calcium, magnesium, potassium and sodium was determined using the X-ray fluorescence method (XRF). The contents of these elements were used to calculate Chemical Index of Alteration (CIA) (Nesbitt & Young, 1982), Chemical Index of Weathering (CIW) (Harnois, 1988), Plagioclase Index of Alteration (PIA) (Fedo et al., 1995), Weathering Index of Parker (WIP) (Parker, 1970), Vogt's Residual Index (V) (Haskins, 2006) values according to the formulas shown in Table 1 (molecular proportions of oxides).The following basic soil analyses were also determined: soil texture by Bouyoucos-Casagrande method modified by Prószyński, total organic carbon (TOC) using the automatic carbon analyser Shimadzu TOC 5000 A, pH in distilled water and 1 M KCl, using the potentiometer method at a soil:liquid ratio of 1:2.5 (v/v), total potential acidity (Hh) using the Kappen method (extraction using 1 mol·dm^{-3} calcium acetate and titration using 0.1 mol·dm^{-3} NaOH), total exchangeable base cations (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}) using 1 M ammonium acetate at pH = 7 and analysed by an atomic absorption spectrometer (Thermoelemental SOLAAR M6). The cation exchange capacity (CEC) and base saturation (BS) were calculated using the sum of total exchangeable base cations (TEB) and potential acidity (Hh). Content of free iron (Fed) using the Mehra and Jackson (1960) extraction procedure and total iron (Fet) by XRF method. The results were arrived at statistically, calculating the coefficients of the correlation between the chemical weathering indicators values and some soil properties.

3. Results

The studied soils display some variability of texture (Table 2) between soil profiles, as well as between genetic horizons in particular profiles. Most of the alluvial soils of the middle Vistula show the light loam texture, while those located on the Żuławy area were finer-grained, with a clayey silt texture according Polish classification PTG 2008 (PTG, 2009). Sandy material occurs in profiles 8 and 11 below 100 cm depth. The vast majority of these soils exhibit a slightly acidic reaction only in the humus horizon of profiles 7 and 11 the pH in 1M KCl reached the value of extremely acidic (3.4) and acidic (4.6), respectively. The base

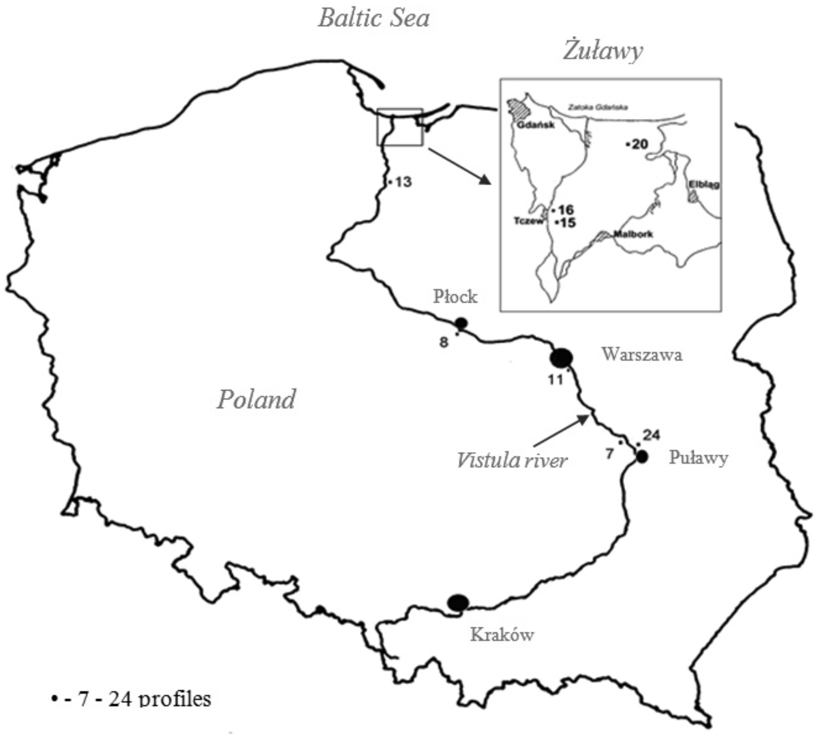

Fig. 1. Location of study area: middle Vistula valley (soil profiles 7, 24, 11, 8 and 13) and Żuławy (profiles 15, 16 and 20)

Table 1
Chemical weathering indices

Index	Formula
Chemical Index of Alteration (CIA)	$CIA = [Al_2O_3/(Al_2O_3 + CaO + Na_2O + K_2O)] \times 100$
Chemical Index of Weathering (CIW)	$CIW = [Al_2O_3/(Al_2O_3 + CaO + Na_2O)] \times 100$
Plagioclase Index of Alteration (PIA)	$PIA = [Al_2O_3 - K_2O /(Al_2O_3 + CaO + Na_2O - K_2O)] \times 100$
Weathering Index of Parker (WIP)	$WIP = [(2 Na_2O/0.35) + (MgO/0.9) + (2K_2O/0.25) + (CaO/0.7)] \times 100$
Vogt's Residual Index (V)	$V = (Al_2O_3 + K_2O)/(MgO + CaO + Na_2O)$

Table 2
Some physical and physico-chemical properties of the investigated solis

Locality profile No	Horizon	Depth [cm]	pH		% particle size distribution [mm]					cmol(+)kg^{-1} of soil			BS	C	Fet	Fed	Fed/ Fet
			H2O	KCl	>2	2–0.05	0.05–0.002	<0.02	<0.002	TEB	Hh	CEC	%				
Alluvial soils of middle Vistula valley Typical proper alluvial soils																	
Gołąb	Ap	0–25	6.5	5.8	0	59	34	21	7	4.40	2.80	7.20	61.11	0.36	1.19	0.39	0.33
near	Ap	25–45	6.9	6.2	0	53	38	22	9	5.09	0.86	5.95	85.54	0.30	1.16	0.33	0.28
Puławy	C1	45–70	7.2	6.2	0	29	56	38	15	9.10	0.76	9.86	92.29	0.53	1.88	0.58	0.31
24	C2	70–100	7.3	6.3	0	51	34	33	15	9.15	0.92	10.07	90.86	0.50	1.74	0.56	0.32
	C3	110–150	7.0	6.0	0	47	42	25	11	5.85	1.00	6.85	85.40	0.25	1.46	0.45	0.31
Zawady	Ap	0–30	5.8	4.6	0	20	59	49	21	10.17	3.60	13.77	73.86	1.81	2.51	0.77	0.31
11	C1	30–58	7.7	6.6	0	19	65	43	16	12.86	0.53	13.39	96.04	0.90	2.30	0.69	0.30
	C2	58–125	7.7	6.5	0	65	28	14	7	5.30	0.45	5.75	92.13	0.42	1.18	0.42	0.35
	C3	130–150	7.4	6.5	0	99	0	1	1	0.62	0.23	0.85	72.94	0.12	0.20	0.07	0.35
Gleyed brown alluvial soils																	
Borek	Ap	0–20	4.8	3.4	0	71	22	13	7	2.14	2.72	4.86	44.03	0.78	0.83	0.26	0.31
7	Bw	20–60	6.1	4.9	0	77	16	10	7	4.02	0.72	4.74	84.81	0.11	0.92	0.28	0.30
	G	150–170	6.8	5.6	0	12	53	71	35	19.43	1.09	20.52	94.68	0.58	3.54	1.03	0.29
Płock	Ap	0–30	7.0	6.4	0	51	37	25	12	14.60	0.67	15.27	95.61	1.11	1.59	0.51	0.32
Radziwie	Bw	30–60	7.2	6.4	0	42	51	31	7	14.93	0.52	15.45	96.63	0.69	1.91	0.61	0.32
8	C1g	60–90	7.1	6.1	0	56	28	34	16	13.60	0.75	14.35	94.77	0.58	2.55	0.95	0.37
	C2rgg	90–120	7.1	6.0	0	57	22	35	21	15.95	0.55	16.50	96.66	0.19	4.02	1.52	0.38
	G	120–130	7.1	6.1	0	99	1	1	0	0.89	0.28	1.17	76.07	0.11	0.25	0.06	0.24
Nebrewo	Ap	0–35	6.8	6.0	0	63	28	24	9	6.88	1.57	8.45	81.42	1.33	1.32	0.46	0.35
Wielkie	Bw	35–75	6.9	5.7	0	44	43	31	13	8.41	1.05	9.46	88.90	0.84	1.73	0.58	0.33
13	C1g	75–135	7.1	5.9	0	49	42	26	9	6.16	0.75	6.91	89.15	0.37	1.42	0.51	0.36
	C2rgg	135–150	7.5	6.3	0	30	53	42	17	11.79	0.71	12.50	94.32	0.68	2.51	0.90	0.36
Alluvial soils of Żuławy Gleyed brown alluvial soils																	
Lisewo	Ap	0–40	7.7	6.7	0	50	35	31	15	14.01	0.60	14.61	95.89	1.18	1.77	0.61	0.34
Malborskie	Bw	40–90	7.7	6.5	0	20	50	65	30	26.10	0.71	26.81	97.35	1.24	4.07	1.29	0.32
16	C1gg	90–130	7.8	6.7	0	31	52	41	17	13.54	0.52	14.06	96.30	0.41	3.24	1.33	0.41
	C2rgg	130–160	7.5	6.4	0	15	56	65	29	18.51	0.75	19.26	96.11	0.49	4.85	1.92	0.39
Gleyed chernozemic alluvial soil																	
Stara	Ap	0–40	7.2	6.3	0	16	38	78	46	27.68	1.24	28.92	95.71	2.62	4.74	1.46	0.31
Wisła	C1g	40–75	7.2	5.9	0	10	41	88	49	27.56	1.01	28.57	96.46	2.46	4.26	0.93	0.22
15	C2rgg	75–120	7.0	5.8	0	12	34	85	54	29.01	1.61	30.62	94.74	2.00	5.63	2.12	0.38
Gley alluvial soil																	
Rybina	Ap	0–20	7.4	6.4	0	20	70	52	10	18.96	0.94	19.90	95.28	1.38	2.53	0.77	0.30
20	C1g	30–60	7.8	6.7	0	12	68	58	20	23.21	0.23	23.44	99.02	0.81	2.71	0.84	0.31
	C2rgg	60–90	7.7	6.6	0	13	62	59	25	26.36	0.49	26.85	98.17	1.30	4.51	1.44	0.32
	G	90–110	7.7	6.7	0	45	37	45	18	17.17	0.45	17.62	97.45	0.63	2.12	0.52	0.24

Explanation: Hh – total potential acidity; TEB – total exchangeable bases; CEC – cation exchange capacity; BS – base saturation; C – soil organic carbon; Fet – total iron, Fed – with dithionite extractable iron (free iron); Fed/Fet – iron mobility index

saturation by alcalic cations fluctuate from 44.3 to 99.2%. The cation exchange capacity usually ranges from 4.74 to 30.62 cmol(+) kg^{-1} of soil attaining the highest values in the alluvial soils from Żuławy and the lowest (below 1 cmol(+) kg^{-1} of soil) in the horizons which display a sand texture. The organic carbon occurs in different amounts of all profiles. The highest content of this element was in gleyed chernozemic alluvial soil (profile 15).

The conducted research showed the following averages and ranges of the chemical weathering indices values in the profiles of the examined soils: CIA – 64.7 (56.1–80.0), CIW – 75.7

(67.3–90.5), PIA – 57.9 (44–77.4), WIP – 25.8 (8.8–36.7) and V – 2.3 (1.8–3.1). However, the mean value of the majority indices in the middle Vistula soils was lower than in the Żuławy soils (Fig. 2, Table 3). Average and ranges of chemical weathering indices values in profiles of typical proper alluvial soils (profiles 11 and 24) and gleyed brown alluvial soils (profiles 7, 8, 13 and 16) were very similar and amounted to: CIA – 62.6 (56.2–69.8), CIW – 74 (71.4–82.2), PIA – 54.9 (44–64.4), WIP – 23.3 (8.8–31.9),

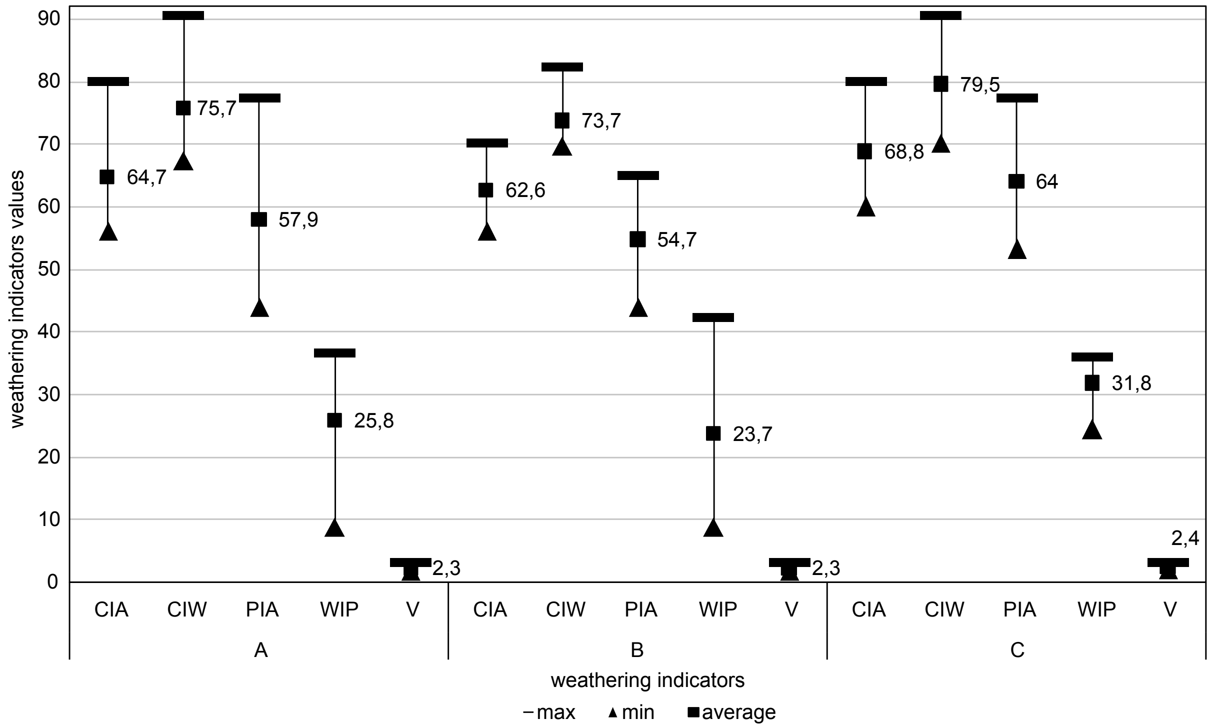

Fig. 2. Average and ranges of chemical weathering indices (CIA, CIW, PIA, WIP, V) in: A – all investigated alluvial soil profiles, B – middle Vistula valley (profiles 7, 24, 11, 8 and 13) and C – Żuławy (profiles 15, 16 and 20)

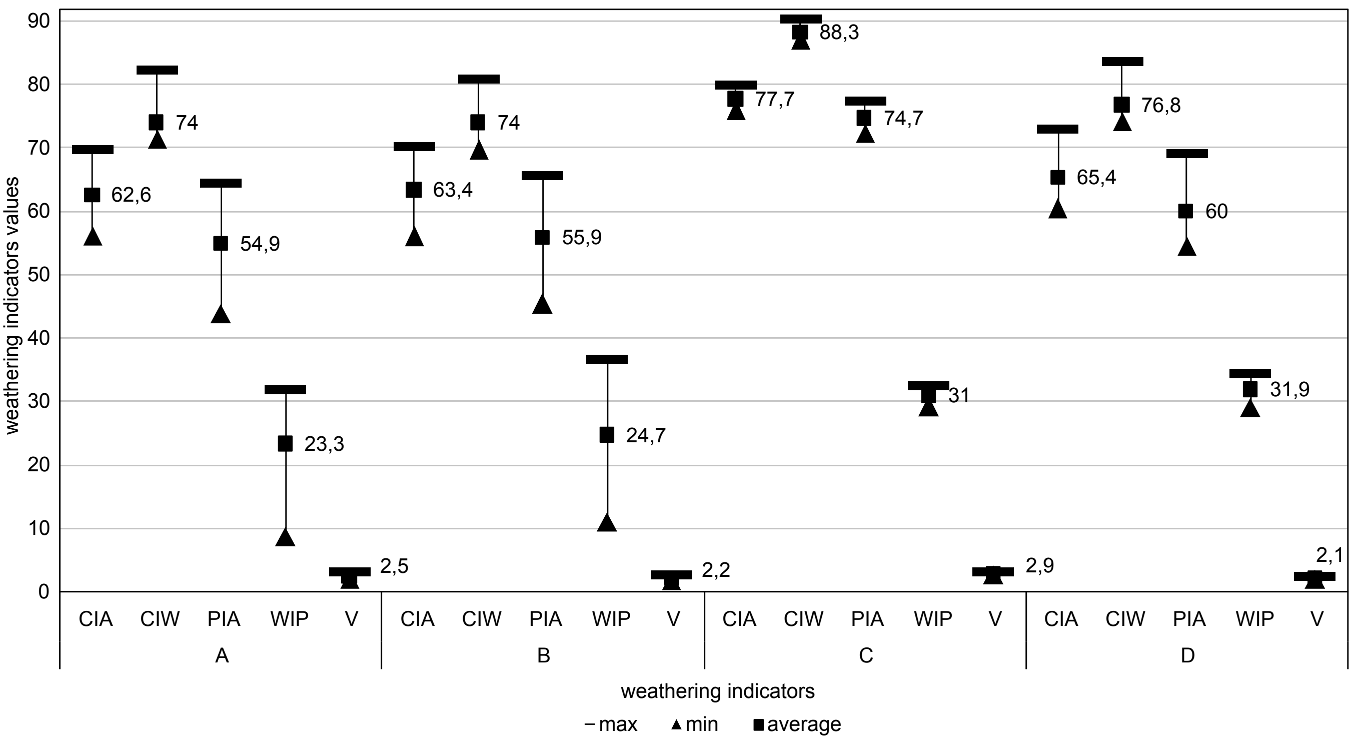

Fig. 3. Means and ranges of chemical weathering indices (CIA, CIW, PIA, WIP, V) in the subtypes alluvial soil profiles of the Vistula valley: Typical proper alluvial soils (A), Gleyed brown alluvial soils (B), Gleyed chernozemic alluvial soil (C) and Gley alluvial soil (D)

V – 2.5 (2–3.2) and CIA – 63.4 (56.1–70.2), CIW – 74 (69.7–81), PIA – 55.9 (45.4–65.6), WIP – 24.7 (11–36.7), V – 2.2 (1.8–2.6), respectively. Slightly larger means and ranges of indices values were found in Gley alluvial soil (profile 20), and the largest in Gleyed chernozemic alluvial soil (profile 15): CIA – 77.7 (76–80), CIW – 88.3 (87.1–90.5), PIA – 74.7 (72.4–77.4), WIP – 31 (29.2–32.5), V – 2.9 (2.8–3.1) (Fig. 3, Table 3). Regardless of the soil-forming processes taking place, low differentiation in the degree weathering of alluvial soils along the middle course of the Vistula was found (Fig. 4).

Table 3
Contents of major oxides and chemical weathering indices values (n=32)

Locality profile No	Horizon	Depth [cm]	%					weathering indicators				
			Al_2O_3	MgO	CaO	Na_2O	K_2O	CIA	CIW	PIA	WIP	V
Alluvial soils of middle Vistula valley Typical proper alluvial soils												
Gołąb	Ap	0–25	5.85	0.44	0.37	0.86	1.38	61.3	73.1	47.7	22.0	2.2
near Puławy	Ap	25–45	5.92	0.45	0.43	0.90	1.43	61.1	72.5	53.7	15.0	2.2
24	C1	45–70	8.43	0.74	0.63	1.07	1.74	63.5	74.0	57.4	27.9	3.2
	C2	70–100	7.61	0.62	0.58	0.96	1.51	69.8	82.2	64.4	24.3	2.9
	C3	110–150	7.01	0.51	0.45	1.14	1.52	62.2	72.6	55.8	25.5	2.2
Zawady	Ap	0–30	10.17	0.96	0.69	1.17	1.98	65.8	76.3	60.3	31.9	2.2
11	C1	30–58	9.54	0.86	0.89	1.25	1.87	62.4	72.1	56.6	31.9	2.0
	C2	58–125	6.02	0.40	0.41	1.06	1.33	61.2	71.4	54.7	23.0	2.2
	C3	125–150	1.87	0.04	0.11	0.30	0.65	56.2	72.0	44.0	8.8	3.1
Gleyed brown alluvial soils												
Borek	Ap	0–20	4.66	0.28	0.23	0.89	1.16	60.0	71.4	52.4	19.0	2.3
7	Bw	20–60	5.21	0.31	0.30	1.02	1.25	60.0	70.8	52.8	21.1	2.2
	G	150–170	14.01	1.47	0.86	1.05	2.43	70.2	81.0	65.1	36.7	2.4
P³ock	Ap	0–30	6.72	0.57	0.91	0.98	1.51	57.9	67.3	51.0	25.6	1.8
Radziwie	Bw	30–60	7.76	0.69	0.89	1.03	1.59	60.8	70.4	50.0	26.8	1.9
8	C1g	60–90	6.71	0.42	0.68	0.69	1.21	65.3	75.0	60.9	19.5	2.4
	C2rgg	90–120	7.44	0.62	0.74	0.59	1.27	69.9	80.0	52.7	18.4	2.6
	G	120–130	2.37	0.07	0.19	0.41	0.79	56.1	69.7	45.4	11.0	2.6
Nebrewo	Ap	0–35	5.34	0.37	0.51	0.83	1.36	59.1	70.3	51.3	20.9	2.1
Wielkie	Bw	35–75	7.05	0.57	0.57	0.98	1.51	67.6	80.2	61.6	24.8	2.1
13	C1g	75–135	6.11	0.42	0.48	0.95	1.38	61.8	72.3	53.5	22.0	2.2
	C2rgg	135–150	9.23	0.79	0.77	1.14	1.85	63.4	73.8	57.4	30.4	2.1
Alluvial soils of Żuławy Gleyed brown alluvial soil												
Lisewo	Ap	0–40	6.77	0.52	0.90	0.89	1.54	60.0	70.2	53.2	24.2	2.0
Malborskie	Bw	40–90	12.37	1.24	1.16	0.92	2.05	69.9	80.1	65.6	31.7	2.3
16	C1gg	90–130	9.31	0.80	0.84	1.13	1.78	63.6	73.4	58.0	29.8	2.1
	C2rgg	130–160	12.23	1.17	0.96	0.98	2.18	68.4	78.8	63.6	32.9	2.3
Gleyed chernozemic alluvial soil												
Stara	Ap	0–40	13.95	1.35	2.02	0.68	2.14	76.0	87.2	72.4	29.2	2.9
Wisła	C1g	40–75	16.55	1.72	1.33	0.76	2.32	77.1	87.1	74.2	32.5	2.8
15	C2rgg	75–120	17.64	1.82	1.52	0.54	2.37	80.0	90.5	77.4	31.3	3.1
Gley alluvial soil												
Rybina	Ap	0–30	9.74	0.96	0.92	1.06	2.02	63.7	74.2	57.8	31.5	2.0
20	C1g	30–60	10.34	1.04	1.06	1.09	2.04	60.5	74.8	54.5	32.6	2.0
	C2rgg	60–90	14.72	1.57	1.42	0.86	2.41	73.1	83.7	69.2	34.3	2.5
	G	90–110	9.24	0.81	0.77	1.07	1.82	64.3	74.4	58.7	29.1	2.1

Explanation: CIA – Chemical Index of Alteration, CIW – Chemical Index of Weathering, PIA – Plagioclase Index of Alteration, WIP – Weathering Index of Parker, V – Vogt's Residual Index

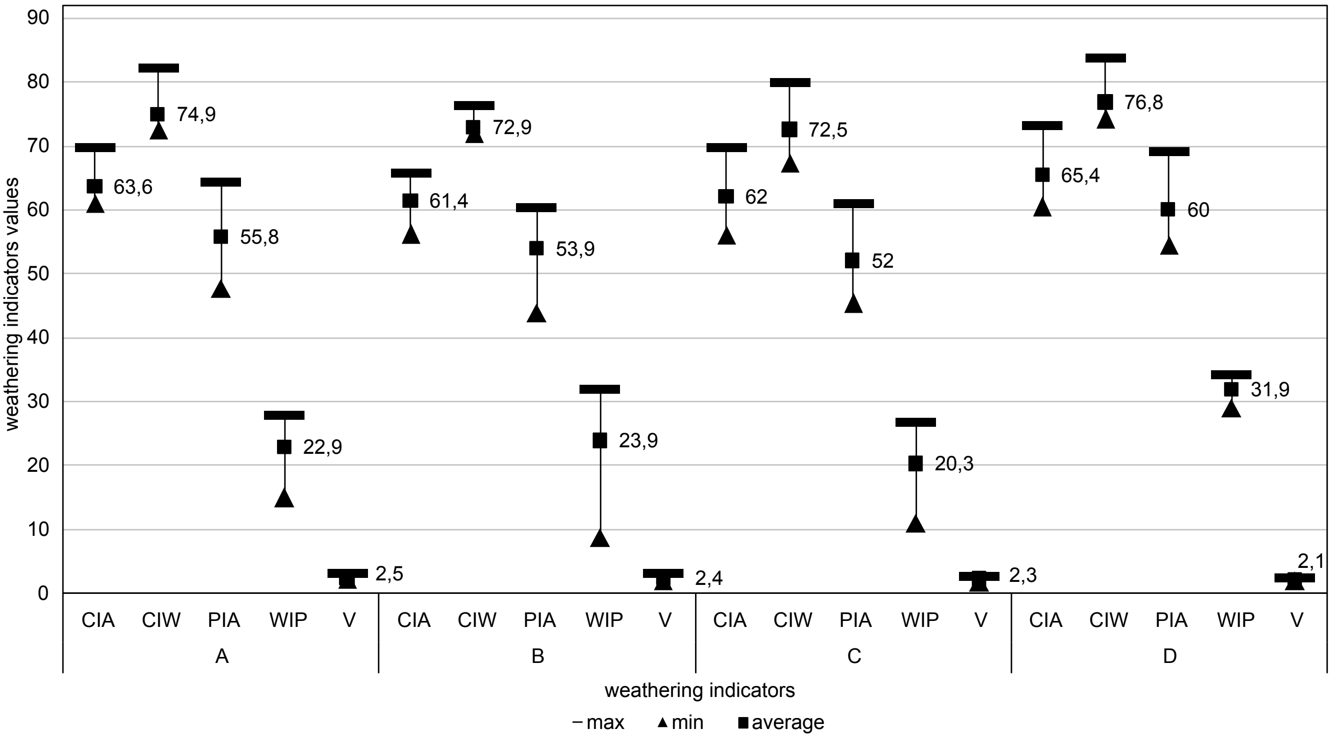

Fig. 4. Means and ranges of weathering indices (CIA, CIW, PIA, WIP, V) in the alluvial soil profiles along the Vistula valley in the distance from the Baltic Sea: 567 km (A), 434 km (B), 309 km (C) and 11 km (D)

In the cross-section of the profiles, the CIA, CIW and PIA indices showed the highest values in the fine-grained horizons, while the smallest in the sand below 100 cm deep (profile 11, 8) (Table 2, 3). Much lower values were obtained for the WIP index, the value of which decreases with increasing soil weathering, while the lowest values were achieved by the V index. Only the gley soil-formation process caused by groundwater, taking place in most alluvial soils, increased the intensity of chemical weathering in the Crgg horizon, that is the accumulation of iron compounds. On the other hand, the processes of humus accumulation, the initiated cambisol development and leaching in the studied soils did not show any influence on their chemical weathering.

4. Discussion

The results of the research showed a relatively low degree of weathering studied soils as well as a small range of its differentiation in the cross-section of the profiles (Table 3, Fig. 2). The classification of weathering proposed by Nesbitt and Young (1982) according to the CIA values (as very slightly weathered (50–60), slightly weathered (60–70), moderately weathered (70–80), highly weathered (80–90), and extremely weathered (90–100)) showed that these soils were slightly weathered. The more intensive weathering of the Żuławy alluvial soils results from their greater fine-grainedness and the content of clay minerals, which are the product of chemical weathering of primary aluminosilicates (orthoclass, plagioclase). This is confirmed by a significant correlation between the content of particles <0.02 mm in diameter and the value of most chemical weathering indices (Table 4).

Compared to the soils developed from old lake sediments containing carbonates in Turkey (Özaytekin et al., 2012; Tunçay et al., 2019) and from limestones (Dengiz et al., 2013), the studied soils showed similar values of weathering indices. However, the intensity of weathering in the cross-section of soil profiles from the area of Turkey was more diverse, and the values of chemical weathering indices decreased or increased with depth. The above-mentioned differences during the weathering process could be caused by different properties of soil alluvial sediments (presence of carbonates) and climatic conditions. A warmer climate with high rainfall significantly increased the intensity of chemical weathering of alluvial soils, among others in valley of the Mississippi (Muhs et al., 2001), the China rivers (Shao et al., 2012) and the Indochina Peninsula rivers (Liu et al., 2007).

Table 4
Coefficients of correlation between chemical weathering indices values and some properties of soils and mobility index of the iron (Fed/Fet)

Variable	CIA	CIW	PIA	WIP	V
< 0.02	0.848**	0.805**	0.878**	0.814**	0.228
< 0.002	0.907**	0.876**	0.899**	0.655**	0.406*
C	0.629**	0.595**	0.690**	0.550**	0.174
Fed/Fet	0.031	0.001	–0.030	–0.052	–0.020

*, ** – significant at a level of p = 0.05 and p = 0.01, respectively

In the cross-sections of the examined soil profiles, no increased chemical weathering was found, which could be caused by a warmer and wetter climate during the Atlantic Holocene period. However, in this period of the Holocene, an increase in the intensity of soil formation processes and chemical weathering was found in the area of the middle Vistula (Baraniecka and Konecka-Betley, 1987; Konecka-Betley, 1991) together with the development of thermophilic vegetation of mixed broadleaf forests (Wasylikowa, 1964; Borówko-Dłużakowa, 1982).

On the other hand, most of the enrichment horizons with iron and manganese compounds (Crgg) generated in the gley soil-forming process showed higher values of chemical weathering indices (profiles 8, 15, 20; Table 3). The released and translocated in this process iron and manganese compounds, and then accumulated just above the groundwater level in the aeration zone, undergo intense chemical changes creating precipitations, concretions and secondary iron and manganese minerals (Chojnicki, 2002; Table 2). It should be assumed that the high dynamics of these processes also stimulates the chemical weathering of aluminosilicates. The poorly advanced soil-forming processes of cambisol development and leaching in the upper layers of some alluvial soils of the middle Vistula did not increase the values of chemical weathering indices. Although the leaching process unlike other soil-forming processes taking place in the studied soils, caused changes in the quantitative occurrence of particular clay minerals. In the humus horizons covered by this process, the highest amounts of illite were found with a simultaneous decrease in the content of smectite and illite-smectite (Chojnicki, 2002).

Relatively small differences in the degree of weathering of the studied soil profiles along the course of the middle Vistula, except for the area of Żuławy (Fig. 4), as well as small ranges of its diversity in the cross-section of the profiles (Table 3) occurred despite the diversified geological structure of its catchment. The sediments of the Vistula valley from Puławy to Warsaw were formed from eroded of the Central Polish glaciation rocks, loess and limestone as well as the soils formed on them, while from Warsaw to the estuary of the eroded substrate of the rocks and soils of the Central Polish and the much younger North Polish Glaciation (Baraniecka and Konecka-Betley, 1987). It seems that the selective removal of mainly fine silt and clay particles took place in the erosion process of rocks and soils (Vaezi et al., 2017). Then, the eroded substrate underwent transformations (segregation, mixing, secondary erosion, weathering) (Safa and Khalid, 2021; Sorokina and Gysev, 2018) as it moved through surface flowing waters. These may have been the main factors that reduced the diversity of properties and susceptibility to chemical weathering of sediments in the Vistula valley.

5. Conclusions

1. The following averages and ranges of the chemical weathering indices values in the Vistula valley and Żuławy alluvial soil profiles were stated: Chemical Index of Alteration (CIA) – 64.7 (56.1–80), Harnois's Chemical Index of Weathering (CIW) – 75.7 (67.3–90.5), Plagioclase Index of Alteration (PIA) – 57.9 (44–77.4), Weathering Index of Parker (WIP) – 25.8 (8.8–36.7) and Vogt's Residual Index (V) – 2.3 (1.8–3.1). The indices reached slightly higher values in the soils of Żuławy than in the middle of the Vistula.
2. The studied soils showed slight weathering determined by the values from 60 to 70 of the most commonly used CIA index. However, the average value of this index in the soils of the middle Vistula slightly exceeded the lower value of this range, while in the soils of Żuławy it was close to the upper value.
3. The gley soil-forming process caused by groundwater, taking place in most soils, increased the intensity of chemical weathering in the horizon of iron and manganese compounds accumulation. While the humus accumulation, poorly advanced cambisol development and leaching soil-forming processes did not increase the values of chemical weathering indices.
4. The weathering indices showed a slight weathering variation of the examined soils in the cross-section of their profiles and along the Vistula valley, despite, as indicated by literature data, the diversity of climatic conditions during the Holocene period and the geological structure of the middle Vistula and Żuławy catchments.

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Chemiczne wietrzenie mad środkowej Wisły i Żuław

Słowa kluczowe

Wietrzenie chemiczne
Mady
Wisła
Żuławy

Streszczenie

Celem pracy było zbadanie intensywności wietrzenia chemicznego w madach uprawnych, obecnie nie zalewanych środkowej Wisły od Puław do Płocka (5 profili) i na obszarze Żuław (3 profile). Badane gleby zaklasyfikowano do: mad właściwych typowych, mad brunatnych gruntowo-glejowych, mad czarnoziemnych gruntowo-glejowych i mad glejowych. Mady środkowej Wisły wykazały przeważnie uziarnienie glin lekkich, natomiast mady Żuław – pyłu ilastego. Ogólną zawartość glinu, wapnia, magnezu, potasu i sodu oznaczono metodą fluorescencji rentgenowskiej (XRF) w próbkach glebowych (średnica <2mm), natomiast podstawowe analizy gleb wykonano metodami stosowanymi powszechnie w laboratoriach gleboznawczych. Stwierdzono następujące średnie i zakresy wartości wskaźników wietrzenia chemicznego profili mad Wisły: chemicznego wskaźnika przemian (CIA) – 64.7 (56.1–80), wskaźnika wietrzenia chemicznego Harnoisa (CIW) – 75.7 (67.3–90.5), wskaźnika przemian plagioklazów (PIA) – 57.9 (44–77.4), wietrzeniowego wskaźnika Parkera (WIP) – 25.8 (8.8–36.7) i wskaźnika Vogta (V) – 2.3 (1.8–3.1), które nieco większe wartości osiągnęły w madach Żuław niż środkowej Wisły. Badane mady wykazały lekkie zwietrzenie określane według wartości najczęściej stosowanego wskaźnika CIA od 60 do 70. Jednak średnia wartość tego wskaźnika w madach środkowej Wisły nieznacznie przekroczyła dolną wartość tego zakresu, natomiast w madach Żuław była zbliżona do wartości górnego zakresu. Gruntowo-glejowy proces glebotwórczy, zachodzący w większości mad, spowodował zwiększenie intensywności wietrzenia chemicznego w poziomach akumulacji związków żelaza, natomiast proces glebotwórczy akumulacji próchnicy i mało zaawansowane brunatnienia i ługowania nie wpłynęły na zwiększenie wartości wskaźników wietrzenia chemicznego. Wskaźniki wietrzenia wykazały małe zróżnicowanie stopnia zwietrzenia mad w przekroju ich profili oraz wzdłuż biegu Wisły, pomimo zróżnicowania warunków klimatycznych w holocenie i budowy geologicznej zlewni środkowej Wisły i Żuław.