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# Soil-forming processes and properties of soils developed from *fluvic* materials in the headwater river valleys of Middle Pomerania, north Poland: A case study of the Kamienna stream

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## Abstract

This study was aimed at characterizing the soil-forming processes and certain properties of soils that have developed from alluvial sediments in the valley of the Kamienna stream, which represents a headwater stream valley deeply incised into the glacial and fluvioglacial deposits of Middle Pomerania, north Poland. Seven soil profiles distributed, along the stream, were described, sampled, and analyzed using standard procedures. The parent materials of the soils showed stratification and were characterized by a sandy texture with considerable admixtures of gravel in some horizons. A textural measures indicated their accumulation in a highly dynamic fluvial environment. The soils showed broad spatial heterogeneity, highlighting the importance of local-scale factors in their formation. The accumulation of soil organic matter (SOM) and gleying from groundwater were identified as major soil-forming processes, which was reflected in soil reference groups distinguished – Eutric Gleyic Fluvisols, Fluvic Gleyic Mollic Umbrisols, Fluvic Gleyic Phaeozems, and Fluvic Phaeozems. The soils were characterized by deep A horizons and high SOM contents. The stratification of these horizons can indicate the partially allochthonous origin of this component, with the headwater bogs in the upper and middle courses of the stream potentially its source. Additionally, the soils were rich in nitrogen, but poor in total P, K, Ca, Mg, Fe, and Al. The generally low contribution of free Fe oxides to the soils indicated poorly advanced weathering, whereas the predominance of amorphous forms of Fe over crystalline could be the effect of high moisture and the SOM content. The soils were also characterized by a low cation exchange capacity, that varied depending on the SOM and clay contents. The soils were generally acidic, with pH values fluctuating around 5.0–7.0, in most cases, although the predominance of acidic over basic ions was not apparent in the sorption complex.

## 1. Introduction

River catchments are open systems that are involved in the biogeochemical cycling of matter and energy. The character and intensity of the geomorphological, hydrological, and other processes in such systems varies over time and space, reflecting catchment characteristics (e.g., the geological structure, relief, and land cover) and the impact of external factors, particularly climate/weather (Andres-Domenech et al., 2015; Bawden et al., 2015). These factors strongly control the flow of water through a catchment and the intensity of the denudation process (Arnell, 1992; Bin Ashraf et al., 2016). River valleys are the most dynamic components of catchments. Such environments, beeing strongly affected by erosion by water and sedimentation. Stratified sediments filling valley bottoms constitute a record of the water–flow dynamics from ancient to modern times (Kobojek, 2009; Szmańda, 2011), and their chemical characteristics have frequently been applied as indicators of human activity (e.g., Czarnowska et al., 1995; Ruiz-Fernandez et al., 2003). In various soil classifications, stratified alluvial sediments have been defined as "*fluvic*" diagnostic materials (e.g., IUSS Working Group WRB, 2015; Classification of the soils of Poland, 6th Edition, 2019) with Fluvisols the typical soils developing from them. However, since earliest studies, it has been assumed that only soils developed from Holocene sediments can be classified as Fluvisols (Strzemski, 1955).

Fluvisols have been the subject of numerous studies, covering a range of aspects. In Poland, such studies have predominantly been focused on the soil–forming processes, and the spatial variability and classification of the soils (e.g., Dobrzański and Nipanicz, 1950; Strzemski, 1955; Reimann and Cieśla, 1961; Witek, 1961; Rytelewski, 1965; Gądor, 1966 a, b; Olszewski et al., 1966; Myślińska and Hoffmann, 1982; Laskowski, 1986; Dąbkowska–Naskręt, 1990; Chojnicki, 2002, 2004; Kabała et al., 2011; Kacprzak et al., 2012; Jonczak, 2015), their physical and chemical properties (e.g. Piszczek et al., 1964; Rytelewski, 1969; Reimann et al., 1975; Mazurski, 1976; Kutyna and Niedźwiecki, 1979; Maszner, 1979; Woźniak, 1995; Orzechowski and Smólczyński, 1998; Chojnicki, 2004; Brogowski and Okołowicz, 2008), mineralogy (e.g. Brogowski and Mazurek, 1986; Dąbkowska-Naskręt, 1990; Długosz et al., 2009; Kabała et al., 2009) and sorptive characteristics (e.g. Siuta, 1963, Orzechowski et al., 2005; Bartkowiak and Długosz, 2010; Kobierski et al., 2010). Their contamination with trace elements is also frequently represented in the literature (Jaworski, 1961; Bojakowska and Sokołowska, 1993; Czarnowska and Bontruk, 1995; Czarnowska et al., 1995; Ciszewski et al., 2004; Kobierski et al., 2008), whereas the aspect of soil organic matter (SOM) has been surprisingly underexplored (Boratyński and Wilk, 1961; Kondratowicz-Maciejewska et al., 2010).

Most of the studies on soils developed from *fluvic* materials concern large and medium-sized river valleys, whereas case studies of small valleys, particularly headwater valleys, are scarce. Meanwhile, the detailed studies of Jonczak (2015) have demonstrated that these areas are specific soil-forming environments. Considering the widespread distribution of headwater areas and their ecological importance (Jekatierynczuk-Rudczyk, 2007; Osadowski, 2010; Wondzell, 2011) and specific features (Mazurek, 2010; Mazurek et al., 2020), the current state of knowledge is not sufficient.

A broad, interdisciplinary study on headwater river valleys in Middle Pomerania (northern Poland) was undertaken by the authors in 2007. Various issues were investigated in the valleys of the Leśna (Florek et al., 2009; Jonczak, 2015), Jarosławianka (Jonczak, 2010; Jonczak and Florek, 2013; Jonczak and Kowalkowski, 2013) and Kamienna catchments (Jonczak et al., 2016; Jonczak and Parzych, 2016; Parzych et al., 2018, 2019; 2020). The study also included examining the features of the soil cover. In this paper, we report the soil-forming processes and certain characteristics of the soils that developed from alluvial sediments in the valley of the Kamienna stream, which represents a headwater stream valley deeply incised into sandy deposits of the Late Pleistocene. The soil properties are discussed in the context of the dynamics of the fluvial environment and headwater character of the valley.

## 2. Materials and methods

### 2.1. Study area

The Kamienna stream is a left-bank tributary of the Słupia River, located north of the Słupsk, in northern Poland (Fig. 1). The young-glacial landscape of the studied area developed as a result of the direct effects of the ice sheet of the Pomeranian Phase of the Vistula Glaciation followed by geomorphological processes in a periglacial zone during the Gardno Phase Glaciation in addition to Holocene processes (Florek, 1991; Kozarski, 1995). The catchment of the Kamienna stream comprises an undulating landscape with predominantly glacial and fluvioglacial sands as surficial deposits. The stream is deeply incised into these deposits, with its bottom beeing covered with fluvial and biogenic sediments. Nowadays, almost the entire area of the catchment is covered by forest with beech, pine and spruce dominating on the plateau, and black alder commonly occurring in the valley bottom. The climate of the studied area is relatively mild due to the influence of the Baltic Sea. The average annual temperature for the period 1950–2007 was 7.6°C and the sum of precipitation was 770 mm (Kirschenstein and Baranowski, 2008). Brunic Arenosols are major components of the soil cover on the plateau, whereas various soil reference groups, developed from *fluvic* materials occur in the stream valley. Histosols are typical components of spring niches that occur mainly along the upper and middle courses of the stream. In 2007 the stream was dammed in its upper and middle courses. Small retention objects cover four small (< 0.1 ha) and two large (about 7 and 3 ha) lakes (Fig. 1). Jonczak and Parzych (2019) showed that damming the water had no great effect on the stream's water chemistry.

### 2.2. Soil sampling and analysis

Seven soil profiles were examined, covering the upper, middle, and lower parts of the valley, (Fig. 1), but being irregularly distributed. The approach adopted enabled us to capture patterns in the soil distribution at the catchment scale, as well as the local (micro-scale) aspects. The soils were described using the criteria set out by the Food and Agriculture Organization of the United Nations (FAO, 2006), and classified according to the WRB system (IUSS Working Group WRB, 2015) and then sampled. One disturbed sample and two undisturbed (100 $cm^3$) samples were taken from each soil horizon. The undisturbed samples were dried at 105°C and weighed. The disturbed samples were air-dried and sieved through a 2.0 mm sieve to remove the gravel fraction. The analysis of the earth fraction included determining the:

- particle-size distribution by mixed pipette and sieve methods. The Polish Soil Science Society (PTG, 2009) classification of textural fractions and groups was applied. Based on those results, geometric measures of texture were calculated after Folk and Ward (1957), including mean diameter (GSS) and sorting (GSO) using Gradistat 5.11 software (Blott and Pye, 2001),
- roundness of the 0.6–0.8 mm quartz grains based on Krygowski (1964). The percentages of the α (well-rounded grains that will roll off a slope of ≤ 8°), β (moderately rounded grains that will roll off a slope of > 8° – 16°) and γ (poorly rounded grains that will roll off a slope of > 16°) grains were recorded, and a roundness index ($W_o$) was calculated based on the data thus obtained,
- bulk density of the undisturbed samples using the gravimetric method,
- specific surface area by glycerin-vapors adsorption,

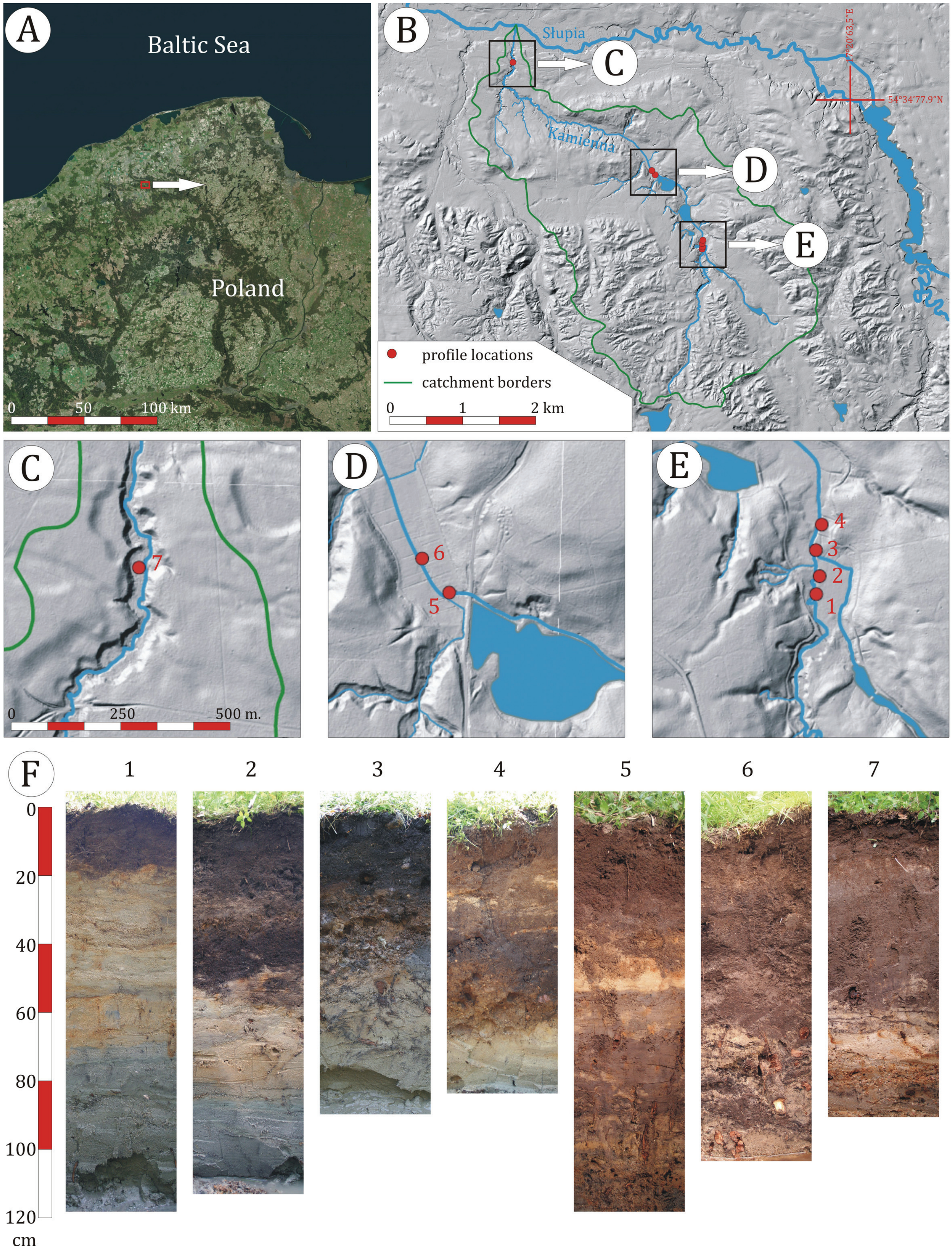

**Fig. 1.** Locations (A–E) and morphology (F) of the studied soils

- pH in a suspension with water and 1 mol $dm^{-3}$ KCl solution in a soil:water/KCl ratio of 1:2.5, using the potentiometric method,
- content of total organic carbon (TOC) and nitrogen (N) by dry combustion (Vario MacroCube, Elementar, Germany),
- total contents of P, K, Ca, Mg, Fe and Al by microwave plasma atomic emission spectroscopy (MP-AES, 4100, Agilent, Australia) after samples digestion in a mixture of 40% HF and 60% $HClO_4$ in a proportion of 3:1 by volume, evaporation of the acids, and dissolution of the residue in 20% HCl,
- content of free Fe ($Fe_d$) using the Mehra and Jackson (1960) extraction procedure, and amorphous Fe ($Fe_o$) and Al ($Al_o$) after extraction by the Shwertmann method (Van Reeuvijk, 1995). The elemental contents of the extracts were determined by MP-AES. Based on those results, the content of crystalline Fe ($Fe_c$) was calculated as $Fe_d – Fe_o$, and,
- exchangeable acidity ($H_w$) and the content of exchangeable Al ($Al_w$) by the Sokolov method, and the exchangeable base contents ($Ca^{2+}$, $Mg^{2+}$, $K^+$ and $Na^+$) by MP-AES after sample extraction in a 1 mol $dm^{-3}$, pH = 7.0 solution of ammonium acetate. Based on those results, the sum of the exchangeable bases (TEB) ($Ca^{2+}$+ $Mg^{2+}$ + $K^+$ + $Na^+$), the cation exchange capacity (CEC) (i.e., $H_w$ + TEB), and base saturation (BS) as (TEB · 100%)/CEC were calculated.

The statistical analysis included obtaining the correlation coefficients between the chosen soil characteristics. Quantum GIS 2.18 software was used to provide spatial visualizations.

## 3. Results

### 3.1. Soil classification and morphology

Accordingly to the WRB (2015) classification, the soils were Eutric Gleyic Fluvisols (profile 1), Fluvic Gleyic Mollic Umbrisols (profiles 2 and 4), Fluvic Gleyic Phaeozems (profile 3) and Fluvic Phaeozems (profiles 5, 6, 7). Parent material stratification, as an inherent feature of soils developed from *fluvic* materials, was observed in all soil profiles. The bottom parts of profiles 1–4 showed features of gleying from groundwater (Fig. 1). The soils differed in terms of the thickness of the A horizon, which ranged from 13 to 88 cm, beeing generally thinner in the upper course of the stream than the middle and lower courses. The A horizon showed stratification in most cases and was characterized by dark coloration (Table 1).

### 3.2. Texture and physical characteristics

The textural characteristics of the soils varied along the stream and with depth. The soils represented sand, loamy sand, and sandy loam textural groups. The sand, silt, and clay textural fractions were 60.0–99.7%, 0.2–33.5%, and 0.0–9.9%, respectively. The soils were usually enriched in the > 2.0 mm fraction. Content of the fraction rarely exceeded 5%, although, in some horizons, it was high, reaching 64.1% in profile 3 (Table 2). The GSS ranged from 55.5 to 569.1 µm. The sediments were usually very poorly to poorly sorted (GSO 1.84–5.81 µm) (Fig. 2). The roundness indicator ($W_o$) of the 0.6–0.8 mm grains generally increased downstream, but showed rather low variability in the soil profiles. Poorly rounded γ type grains strongly predominated in all the soils, followed by β type (moderately rounded) and small amounts of α type (well rounded) grains (Table 2).

The bulk density of the soils ranged from 0.91 to 1.76 g $cm^{-3}$, showing a very strong negative correlation (–0.902) with TOC content, and strong with GSO ($R^2$ = –0.542). Generally, the A horizons were characterized by lower density than the parent material. The specific surface area varied from 3.50 to 31.42 $m^2$ $g^{-1}$ (Table 1), and it was correlated with the GSS ($R^2$ = –0.657), clay content ($R^2$ = 0.684), and TOC ($R^2$ = 0.532).

### 3.3. Soil pH and content of organic carbon and major nutrients

The topsoil samples were very strongly and strongly acidic, with pH–$H_2O$ values ranging from 3.9 to 5.5 and pH–KCl values from 3.0 to 4.1. The depth tendencies varied among the profiles, with rapid increases in pH beeing recorded in profiles 1 and 4, whereas this trend was not so clear in profiles 3 and 5–7 (Table 1). Irregular changes were noted in profile 2. Although the pH in some of the horizons was close to neutral or alkaline, there were no carbonates in the samples.

The soils were generally rich in TOC, the content varying from 8.34 to 53.29 g $kg^{-1}$ in the A horizons and from 0.45 to 16.94 g $kg^{-1}$ in the remaining horizons. The TOC stocks at depth of 0–150 cm in profiles 1–7 were, respectively 4.97, 17.48, 16.21, 15.17, 24.45, 29.31, and 13.59 kg $m^{-2}$. Nitrogen occurred in amounts of 0.04–3.60 g $kg^{-1}$, reaching its maximum in the A horizons, and being very strongly positively correlated with TOC ($R^2$ = 0.976). The TOC:N ratios varied from 4.6:1 to 20.6:1, with the lowest values being typical for C horizons, and the highest occurring in the topsoil of profile 3. In the A horizons, the ratio usually fluctuated around 11–14. Phosphorus showed lower variability than N, occurring in amounts of 0.14–0.75 g $kg^{-1}$ and being correlated with TOC ($R^2$ = 0.540). The total Ca content was low, rarely exceeding 3.00 g $kg^{-1}$ and reaching a maximum of 5.69 g $kg^{-1}$ (Table 3). No clear tendencies were observed in the elemental distributions, either spatially or in the profiles. However, Ca was positively correlated with Mg ($R^2$ = 0.679), but the Ca content was 1.2–3.9 times lower, fluctuating between 0.49 and 3.20 g $kg^{-1}$ (Table 3).

### 3.4. Forms of iron and aluminum

Total Fe content varied from 2.75 to 15.30 g $kg^{-1}$ (Table 4), showing great variability within the soil profiles, accompanied by low spatial variability. The Fe was positively correlated with the clay fraction ($R^2$ = 0.550). The $Fe_d$ amounted to 0.19–11.31 g $kg^{-1}$, constituting 3.0–77.1% of the $Fe_t$. In all the soils, the highest $Fe_d$ contents and $Fe_d/Fe_t$ ratios were noted in the topsoil, and had a general decreasing tendency with depth. Amorphous Fe oxides ($Fe_o$) predominated over crystalline forms in most cases,

**Table 1**
Basic physical characteristics and pH of the studied soils

| Horizon | Depth [cm] | Munsell soil color (wet) | Bulk density g cm$^{-3}$ | Specific surface area m$^2$ g$^{-1}$ | pH-H$_2$O | pH-KCl |
|---|---|---|---|---|---|---|
| Profile 1 – Eutric Gleyic Fluvisol | | | | | | |
| Ah | 0–13 | 10YR 3/2 | 1.20 | 16.1 | 4.1 | 3.4 |
| Cg1 | 13–43 | 2.5Y 6/4 | 1.67 | 10.4 | 5.7 | 3.9 |
| Cg2 | 43–49 | 5Y 2/2.5 | 1.63 | 18.4 | 5.6 | 3.7 |
| Cg3 | 49–65 | 7.5Y 5/1.5 | 1.69 | 5.7 | 5.9 | 4.4 |
| Cr1 | 65–68 | 5Y 5/2 | – | 4.1 | 5.7 | 4.6 |
| Cr2 | 68–70 | 10Y 5/1 | – | 21.6 | 6.9 | 5.5 |
| Cr3 | 70–79 | 10Y 4.5/1 | 1.63 | 8.7 | 7.1 | 5.9 |
| Cr4 | 79–83 | 10Y 4/1 | 1.59 | 26.9 | 7.8 | 6.3 |
| Cr5 | 83–150 | 10Y 4/1 | 1.66 | 6.6 | 7.2 | 5.9 |
| Profile 2 – Fluvic Gleyic Mollic Umbrisol | | | | | | |
| Ah1 | 0–22 | 10YR 2/2 | 1.08 | 21.3 | 3.9 | 3.0 |
| Ah2 | 22–30 | 10YR 3/3 | 1.38 | 20.3 | 4.8 | 3.5 |
| Ah3 | 30–41 | 10YR 2/2 | 1.00 | 21.1 | 4.9 | 3.8 |
| C | 41–70 | 2.5Y 5/3 | 1.74 | 7.1 | 6.2 | 4.8 |
| Cr1 | 70–80 | 5Y 4.5/2 | 1.67 | 5.4 | 4.2 | 3.2 |
| Cr2 | 80–83 | 2.5GY 5/1 | 1.55 | 17.4 | 7.2 | 5.7 |
| Cr3 | 83–150 | 7.5Y 5/1 | 1.66 | 5.8 | 4.5 | 3.7 |
| Profile 3 – Fluvic Gleyic Phaeozem | | | | | | |
| Ah | 0–24 | 10YR 1.7/1 | 1.15 | 7.9 | 5.5 | 4.1 |
| C | 24–60 | 10YR 2/3 | 1.56 | 11.2 | 5.6 | 4.2 |
| Cr | 60–150 | 5Y 4/2 | 1.76 | 10.2 | 6.0 | 4.5 |
| Profile 4 – Fluvic Gleyic Mollic Umbrisol | | | | | | |
| Ah1 | 0–15 | 10YR 2/3 | 1.16 | 17.3 | 4.1 | 3.3 |
| Ah2 | 15–39 | 10YR 2/1.5 | 1.28 | 8.7 | 5.3 | 4.0 |
| Ah3 | 39–51 | 10YR 1.7/1 | 0.91 | 18.6 | 5.3 | 4.4 |
| AC | 51–60 | 10YR 3.5/3 | 1.44 | 10.4 | 6.6 | 5.5 |
| Cr | 60–150 | 5Y 6/2.5 | 1.73 | 7.9 | 6.8 | 5.2 |
| Profile 5 – Fluvic Phaeozem | | | | | | |
| Ah | 0–40 | 10YR 2/3 | 0.98 | 19.7 | 4.4 | 3.4 |
| C | 40–53 | 10YR 5.5/4 | 1.45 | 8.3 | 5.4 | 4.1 |
| A1 | 53–70 | 10YR 3/2 | 1.36 | 16.8 | 5.4 | 3.6 |
| A2 | 70–88 | 10YR 2/3 | 1.21 | 21.3 | 5.0 | 4.1 |
| Cg | 88–100 | 10YR 5/4 | 1.40 | 5.0 | 5.8 | 4.7 |
| Cr | 100–150 | 2.5Y 4/4 | 1.39 | 4.2 | 5.8 | 4.7 |
| Profile 6 – Fluvic Phaeozem | | | | | | |
| Ah1 | 0–25 | 10YR 2.5/3 | 1.08 | 16.5 | 4.1 | 3.3 |
| Ah2 | 25–65 | 10YR 2/3 | 0.91 | 16.6 | 5.5 | 4.1 |
| A/Cg | 65–94 | 10YR 4/2 | 1.37 | 14.5 | 5.8 | 4.8 |
| Cr | 94–150 | 10YR 4/2 | 1.60 | 3.5 | 6.0 | 5.2 |
| Profile 7 – Fluvic Phaeozem | | | | | | |
| Ah1 | 0–20 | 10YR 2.5/3 | 1.27 | 29.7 | 3.9 | 3.0 |
| Ah2 | 20–53 | 10YR 2/3 | 1.17 | 31.4 | 4.7 | 3.7 |
| Cg1 | 53–68 | 10YR 5/3.5 | 1.39 | 10.0 | 5.1 | 3.9 |
| Cg2 | 68–82 | 10YR 5/4 | 1.59 | 10.9 | 5.2 | 3.9 |
| Cr | 82–150 | 10YR 5/3 | 1.61 | 5.2 | 5.7 | 3.4 |

**Table 2**
Particle-size distribution and rounding of 0.6–0.8 mm grains

| Horizon | Depth [cm] | Content of textural fractions [mm] | | | | | Rounding (% of grain type) | | | $W_o$ |
|---|---|---|---|---|---|---|---|---|---|---|
| | | >2.0% | 2.0–0.05 % | 0.05–0.002 % | <0.002 % | Textural group* | α | β | γ | |
| Profile 1 – Eutric Gleyic Fluvisol | | | | | | | | | | |
| Ah | 0–13 | 1.3 | 82.6 | 13.0 | 4.4 | LS | 5.1 | 32.3 | 62.7 | 668 |
| Cg1 | 13–43 | 1.6 | 90.2 | 6.5 | 3.3 | S | 6.2 | 18.6 | 75.2 | 477 |
| Cg2 | 43–49 | 0.0 | 74.1 | 19.3 | 6.6 | SL | 7.4 | 20.6 | 72.0 | 545 |
| Cg3 | 49–65 | 2.2 | 97.4 | 1.0 | 1.6 | S | 4.0 | 18.7 | 77.3 | 450 |
| Cr1 | 65–68 | 2.1 | 97.1 | 1.5 | 1.4 | S | 4.3 | 11.7 | 84.0 | 447 |
| Cr2 | 68–70 | 0.7 | 60.0 | 33.5 | 6.5 | SL | 5.0 | 16.0 | 79.0 | 498 |
| Cr3 | 70–79 | 0.3 | 95.0 | 3.7 | 1.3 | S | 3.6 | 17.8 | 78.6 | 551 |
| Cr4 | 79–83 | 0.7 | 67.4 | 22.9 | 9.7 | SL | 5.9 | 22.7 | 71.4 | 656 |
| Cr5 | 83–150 | 2.8 | 97.4 | 1.7 | 0.9 | S | 3.4 | 28.9 | 67.7 | 668 |
| Profile 2 – Fluvic Gleyic Mollic Umbrisol | | | | | | | | | | |
| Ah1 | 0–22 | 2.1 | 74.1 | 19.8 | 6.1 | SL | 5.0 | 26.5 | 68.4 | 619 |
| Ah2 | 22–30 | 1.5 | 80.2 | 14.7 | 5.1 | LS | 4.1 | 24.3 | 71.6 | 543 |
| Ah3 | 30–41 | 2.7 | 89.5 | 4.6 | 5.9 | S | 2.5 | 21.4 | 76.1 | 535 |
| C | 41–70 | 2.1 | 96.6 | 2.4 | 1.0 | S | 4.3 | 17.7 | 78.0 | 617 |
| Cr1 | 70–80 | 7.0 | 94.9 | 3.2 | 1.9 | S | 2.8 | 29.4 | 67.8 | 610 |
| Cr2 | 80–83 | 0.2 | 75.4 | 18.6 | 6.0 | SL | 3.7 | 15.3 | 81.0 | 461 |
| Cr3 | 83–150 | 0.3 | 97.1 | 2.0 | 0.9 | S | 4.8 | 24.5 | 70.6 | 642 |
| Profile 3 – Fluvic Gleyic Phaeozem | | | | | | | | | | |
| Ah | 0–24 | 18.1 | 95.7 | 3.0 | 1.3 | S | 3.8 | 27.4 | 68.7 | 642 |
| C | 24–60 | 64.1 | 96.0 | 3.5 | 0.5 | S | 6.3 | 24.8 | 68.9 | 645 |
| Cr | 60–150 | 0.6 | 96.2 | 3.1 | 0.7 | S | 3.9 | 22.8 | 73.3 | 602 |
| Profile 4 – Fluvic Gleyic Mollic Umbrisol | | | | | | | | | | |
| Ah1 | 0–15 | 2.5 | 84.1 | 12.6 | 3.3 | LS | 4.8 | 21.6 | 73.6 | 610 |
| Ah2 | 15–39 | 5.2 | 89.1 | 9.4 | 1.5 | S | 7.1 | 25.3 | 67.6 | 728 |
| Ah3 | 39–51 | 8.8 | 80.9 | 13.4 | 5.7 | LS | 6.4 | 34.3 | 59.4 | 810 |
| AC | 51–60 | 47.6 | 93.7 | 6.0 | 0.3 | S | 6.3 | 33.8 | 59.9 | 790 |
| Cr | 60–80 | 1.1 | 95.6 | 2.5 | 1.9 | S | 3.3 | 33.7 | 63.0 | 710 |
| Profile 5 – Fluvic Phaeozem | | | | | | | | | | |
| Ah | 0–40 | 1.8 | 75.8 | 18.0 | 6.2 | SL | 5.1 | 22.1 | 72.8 | 678 |
| C | 40–53 | 0.5 | 97.3 | 2.0 | 0.7 | S | 4.7 | 24.8 | 70.5 | 666 |
| A1 | 53–70 | 0.0 | 77.3 | 16.5 | 6.2 | SL | 4.0 | 32.0 | 64.0 | 748 |
| A2 | 70–88 | 0.0 | 79.6 | 16.4 | 4.0 | S | 8.2 | 19.9 | 71.9 | 701 |
| Cg | 88–100 | 7.2 | 98.7 | 0.6 | 0.7 | S | 6.8 | 45.5 | 47.8 | 817 |
| Cr | 100–150 | 16.0 | 97.8 | 1.7 | 0.5 | S | 6.5 | 40.2 | 53.3 | 863 |
| Profile 6 – Fluvic Phaeozem | | | | | | | | | | |
| Ah1 | 0–25 | 2.7 | 78.3 | 11.8 | 9.9 | SL | 8.8 | 28.6 | 62.6 | 763 |
| Ah2 | 25–65 | 0.0 | 74.3 | 19.9 | 5.8 | SL | 2.7 | 21.6 | 75.7 | 624 |
| A/Cg | 65–94 | 2.4 | 97.9 | 2.0 | 0.1 | S | 6.3 | 34.8 | 58.9 | 804 |
| Cr | 94–150 | 10.7 | 99.7 | 0.2 | 0.1 | S | 2.6 | 30.9 | 66.4 | 707 |
| Profile 7 – Fluvic Phaeozem | | | | | | | | | | |
| Ah1 | 0–20 | 0.0 | 76.4 | 20.3 | 3.3 | LS | 6.9 | 33.7 | 59.4 | 823 |
| Ah2 | 20–53 | 0.0 | 78.7 | 19.2 | 2.1 | LS | 3.7 | 33.3 | 63.0 | 767 |
| Cg1 | 53–68 | 1.0 | 97.5 | 2.1 | 0.4 | S | 3.0 | 36.3 | 60.7 | 824 |
| Cg2 | 68–82 | 24.9 | 99.5 | 0.4 | 0.1 | S | 6.0 | 23.0 | 71.0 | 702 |
| Cr | 82–150 | 5.3 | 99.7 | 0.3 | 0.0 | S | 9.3 | 44.1 | 46.6 | 908 |

* PTG (2009), LS – loamy sand; S – sand; SL – sandy loam

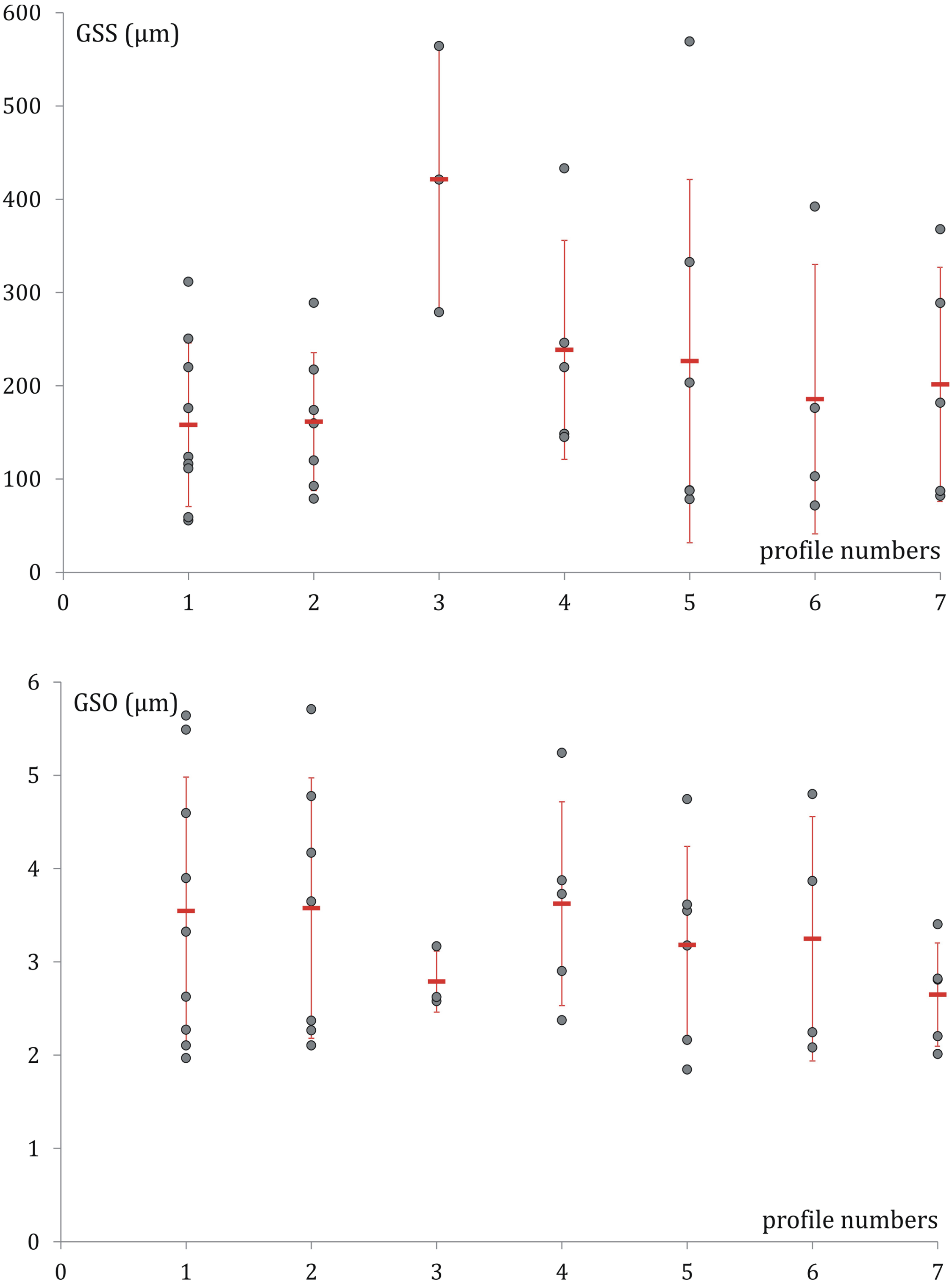

**Fig. 2.** Mean diameter (GSS) and sorting (GSO) of the studied soils (in red mean values ± SD in soil profiles)

as evidenced by the $Fe_c/Fe_d$ ratios, which were usually <0.5 (Table 4). However, various depth tendencies were observed in the profiles. There was a positive correlation between the content of $Fe_o$ and TOC ($R^2 = 0.662$) highlighting the importance of SOM as a factor in sesquioxide crystallization.

The $Al_t$ contents were at least twice as high as the $Fe_t$, varying from 12.08 to 29.56 g kg$^{-1}$ (Table 4). Both elements were positively correlated ($R^2 = 0.686$), thus having similar depth and spatial tendencies. Also, $Al_t$ was positively correlated with clay ($R^2 = 0.702$). The $Al_o$ constituted 4.0–27.8% of its total form. The $Al_o/Al_t$ ratios were usually highest in the topsoil, decreasing down through the profiles.

**Table 3**
Total content of TOC and major nutrients in the studied soils

| Horizon | Depth [cm] | TOC g kg$^{-1}$ | N g kg$^{-1}$ | P g kg$^{-1}$ | K g kg$^{-1}$ | Ca g kg$^{-1}$ | Mg g kg$^{-1}$ | TOC:N | TOC:P |
|---|---|---|---|---|---|---|---|---|---|
| Profile 1 – Eutric Gleyic Fluvisol | | | | | | | | | |
| Ah | 0–13 | 21.63 | 2.00 | 0.28 | 10.70 | 1.59 | 1.15 | 10.8 | 78.7 |
| Cg1 | 13–43 | 0.59 | 0.06 | 0.14 | 11.06 | 2.00 | 1.11 | 10.2 | 4.3 |
| Cg2 | 43–49 | 2.18 | 0.19 | 0.17 | 14.24 | 2.75 | 2.23 | 11.5 | 12.6 |
| Cg3 | 49–65 | 0.53 | 0.08 | 0.16 | 9.68 | 1.97 | 0.83 | 6.6 | 3.2 |
| Cr1 | 65–68 | 0.52 | 0.07 | 0.29 | 9.18 | 2.06 | 0.79 | 7.2 | 1.8 |
| Cr2 | 68–70 | 1.72 | 0.21 | 0.33 | 15.76 | 3.41 | 2.64 | 8.1 | 5.2 |
| Cr3 | 70–79 | 0.59 | 0.05 | 0.21 | 11.18 | 2.04 | 0.88 | 11.4 | 2.8 |
| Cr4 | 79–83 | 4.46 | 0.42 | 0.40 | 15.59 | 3.80 | 3.20 | 10.5 | 11.1 |
| Cr5 | 83–150 | 0.45 | 0.04 | 0.28 | 9.07 | 2.22 | 0.72 | 11.4 | 1.6 |
| Profile 2 – Fluvic Gleyic Mollic Umbrisol | | | | | | | | | |
| Ah1 | 0–22 | 38.45 | 2.79 | 0.57 | 10.56 | 1.77 | 1.53 | 13.8 | 67.2 |
| Ah2 | 22–30 | 18.31 | 1.07 | 0.31 | 10.41 | 2.16 | 1.17 | 17.2 | 59.3 |
| Ah3 | 30–41 | 45.29 | 2.92 | 0.18 | 9.42 | 3.04 | 0.79 | 15.5 | 255.5 |
| C | 41–70 | 0.84 | 0.06 | 0.20 | 10.76 | 2.07 | 0.85 | 13.4 | 4.2 |
| Cr1 | 70–80 | 0.91 | 0.09 | 0.27 | 11.13 | 2.14 | 1.10 | 10.1 | 3.4 |
| Cr2 | 80–83 | 1.98 | 0.20 | 0.31 | 15.11 | 3.36 | 2.03 | 9.7 | 6.5 |
| Cr3 | 83–150 | 0.58 | 0.06 | 0.19 | 9.85 | 2.03 | 0.80 | 10.3 | 3.0 |
| Profile 3 – Fluvic Gleyic Phaeozem | | | | | | | | | |
| Ah | 0–24 | 19.41 | 0.94 | 0.15 | 9.83 | 2.77 | 1.06 | 20.6 | 126.5 |
| C | 24–60 | 16.94 | 0.82 | 0.75 | 11.25 | 4.67 | 2.64 | 20.6 | 22.5 |
| Cr | 60–150 | 0.68 | 0.10 | 0.26 | 10.09 | 2.18 | 0.98 | 7.2 | 2.6 |
| Profile 4 – Fluvic Gleyic Mollic Umbrisol | | | | | | | | | |
| Ah1 | 0–15 | 22.36 | 1.99 | 0.52 | 10.71 | 2.19 | 1.47 | 11.2 | 42.9 |
| Ah2 | 15–39 | 8.34 | 0.76 | 0.33 | 10.27 | 2.33 | 1.18 | 11.0 | 25.6 |
| Ah3 | 39–51 | 53.29 | 3.49 | 0.44 | 9.76 | 4.35 | 1.27 | 15.3 | 121.6 |
| AC | 51–60 | 14.80 | 0.81 | 0.65 | 9.97 | 4.41 | 2.52 | 18.3 | 22.8 |
| Cr | 60–150 | 0.52 | 0.11 | 0.24 | 10.27 | 1.80 | 1.02 | 4.6 | 2.1 |
| Profile 5 – Fluvic Phaeozem | | | | | | | | | |
| Ah | 0–40 | 41.14 | 3.60 | 0.71 | 11.90 | 2.82 | 1.92 | 11.4 | 58.1 |
| C | 40–53 | 3.65 | 0.25 | 0.46 | 8.81 | 1.55 | 0.54 | 14.8 | 7.9 |
| A1 | 53–70 | 8.88 | 0.64 | 0.32 | 12.09 | 3.00 | 1.47 | 13.9 | 28.0 |
| A2 | 70–88 | 16.49 | 1.37 | 0.30 | 12.56 | 3.36 | 1.56 | 12.0 | 54.3 |
| Cg | 88–100 | 2.11 | 0.15 | 0.18 | 10.39 | 2.04 | 0.54 | 14.2 | 11.9 |
| Cr | 100–150 | 2.29 | 0.16 | 0.27 | 11.60 | 2.45 | 0.87 | 14.5 | 8.4 |
| Profile 6 – Fluvic Phaeozem | | | | | | | | | |
| Ah1 | 0–25 | 32.47 | 2.97 | 0.61 | 11.58 | 2.72 | 1.57 | 11.0 | 53.2 |
| Ah2 | 25–65 | 39.79 | 3.23 | 0.49 | 11.77 | 5.69 | 1.65 | 12.3 | 81.0 |
| A/Cg | 65–94 | 12.92 | 0.83 | 0.20 | 10.19 | 2.50 | 0.64 | 15.6 | 63.5 |
| Cr | 94–150 | 0.95 | 0.09 | 0.19 | 8.32 | 1.62 | 0.49 | 10.2 | 5.1 |
| Profile 7 – Fluvic Phaeozem | | | | | | | | | |
| Ah1 | 0–20 | 17.44 | 1.63 | 0.60 | 12.82 | 2.21 | 1.65 | 10.7 | 29.2 |
| Ah2 | 20–53 | 19.00 | 1.82 | 0.52 | 13.22 | 3.45 | 1.79 | 10.4 | 36.9 |
| Cg1 | 53–68 | 3.19 | 0.29 | 0.16 | 9.59 | 1.86 | 0.65 | 11.0 | 20.0 |
| Cg2 | 68–82 | 2.02 | 0.20 | 0.32 | 8.77 | 1.77 | 0.66 | 10.2 | 6.4 |
| Cr | 82–150 | 0.64 | 0.11 | 0.16 | 7.63 | 1.48 | 0.54 | 5.7 | 4.0 |

**Table 4**
Iron and aluminum forms in the studied soils

| Horizon | Depth [cm] | $Fe_t$ g kg$^{-1}$ | $Fe_d$ g kg$^{-1}$ | $Fe_o$ g kg$^{-1}$ | $Fe_c$ g kg$^{-1}$ | $Fe_d/Fe_t$ | $Fe_c/Fe_d$ | $Al_t$ g kg$^{-1}$ | $Al_o$ g kg$^{-1}$ | $Al_o/Al_t$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Profile 1 – Eutric Gleyic Fluvisol | | | | | | | | | | |
| Ah | 0–13 | 10.22 | 7.36 | 5.81 | 1.55 | 0.72 | 0.21 | 20.50 | 1.98 | 0.10 |
| Cg1 | 13–43 | 5.52 | 1.76 | 0.92 | 0.84 | 0.32 | 0.48 | 18.11 | 0.36 | 0.02 |
| Cg2 | 43–49 | 9.35 | 0.93 | 0.47 | 0.46 | 0.10 | 0.50 | 24.76 | 0.38 | 0.02 |
| Cg3 | 49–65 | 4.48 | 1.10 | 0.64 | 0.47 | 0.25 | 0.42 | 15.12 | 0.11 | 0.01 |
| Cr1 | 65–68 | 5.01 | 0.51 | 0.28 | 0.23 | 0.10 | 0.45 | 14.54 | 0.09 | 0.01 |
| Cr2 | 68–70 | 11.18 | 0.58 | 0.32 | 0.26 | 0.05 | 0.44 | 27.86 | 0.35 | 0.01 |
| Cr3 | 70–79 | 4.66 | 0.19 | 0.16 | 0.03 | 0.04 | 0.18 | 16.24 | 0.10 | 0.01 |
| Cr4 | 79–83 | 11.99 | 0.66 | 0.29 | 0.37 | 0.06 | 0.56 | 29.56 | 0.39 | 0.01 |
| Cr5 | 83–150 | 3.88 | 0.21 | 0.19 | 0.02 | 0.05 | 0.09 | 14.79 | 0.05 | 0.00 |
| Profile 2 – Fluvic Gleyic Mollic Umbrisol | | | | | | | | | | |
| Ah1 | 0–22 | 14.87 | 11.31 | 9.38 | 1.93 | 0.76 | 0.17 | 23.46 | 1.83 | 0.08 |
| Ah2 | 22–30 | 12.99 | 7.87 | 3.03 | 4.83 | 0.61 | 0.61 | 24.03 | 1.19 | 0.05 |
| Ah3 | 30–41 | 5.89 | 3.07 | 2.21 | 0.86 | 0.52 | 0.28 | 19.76 | 1.67 | 0.08 |
| C | 41–70 | 5.51 | 0.78 | 0.60 | 0.18 | 0.14 | 0.23 | 16.97 | 0.18 | 0.01 |
| Cr1 | 70–80 | 7.14 | 0.87 | 0.63 | 0.24 | 0.12 | 0.28 | 17.82 | 0.19 | 0.01 |
| Cr2 | 80–83 | 9.19 | 0.28 | 0.23 | 0.05 | 0.03 | 0.16 | 24.99 | 0.34 | 0.01 |
| Cr3 | 83–150 | 5.38 | 0.70 | 0.47 | 0.23 | 0.13 | 0.33 | 15.54 | 0.13 | 0.01 |
| Profile 3 – Fluvic Gleyic Phaeozem | | | | | | | | | | |
| Ah | 0–24 | 6.19 | 1.74 | 1.02 | 0.73 | 0.28 | 0.42 | 19.97 | 4.89 | 0.24 |
| C | 24–60 | 11.66 | 1.41 | 0.99 | 0.42 | 0.12 | 0.30 | 26.38 | 4.77 | 0.18 |
| Cr | 60–150 | 5.34 | 0.31 | 0.29 | 0.01 | 0.06 | 0.04 | 15.74 | 0.22 | 0.01 |
| Profile 4 – Fluvic Gleyic Mollic Umbrisol | | | | | | | | | | |
| Ah1 | 0–15 | 10.08 | 7.20 | 4.03 | 3.17 | 0.71 | 0.44 | 19.72 | 1.71 | 0.09 |
| Ah2 | 15–39 | 6.81 | 2.99 | 1.82 | 1.17 | 0.44 | 0.39 | 17.86 | 1.04 | 0.06 |
| Ah3 | 39–51 | 8.24 | 4.57 | 3.06 | 1.50 | 0.55 | 0.33 | 20.09 | 3.90 | 0.19 |
| AC | 51–60 | 15.30 | 6.06 | 2.82 | 3.23 | 0.40 | 0.53 | 26.55 | 7.37 | 0.28 |
| Cr | 60–150 | 5.57 | 0.43 | 0.33 | 0.10 | 0.08 | 0.24 | 16.76 | 0.41 | 0.02 |
| Profile 5 – Fluvic Phaeozem | | | | | | | | | | |
| Ah | 0–40 | 12.20 | 8.16 | 4.83 | 3.33 | 0.67 | 0.41 | 24.71 | 2.65 | 0.11 |
| C | 40–53 | 7.26 | 4.62 | 2.54 | 2.08 | 0.64 | 0.45 | 13.61 | 0.88 | 0.07 |
| A1 | 53–70 | 8.49 | 1.79 | 1.10 | 0.70 | 0.21 | 0.39 | 22.64 | 0.61 | 0.03 |
| A2 | 70–88 | 8.42 | 2.19 | 1.27 | 0.92 | 0.26 | 0.42 | 22.89 | 0.75 | 0.03 |
| Cg | 88–100 | 2.75 | 0.52 | 0.35 | 0.16 | 0.19 | 0.31 | 17.11 | 0.13 | 0.01 |
| Cr | 100–150 | 6.79 | 1.33 | 0.75 | 0.58 | 0.20 | 0.44 | 18.33 | 0.13 | 0.01 |
| Profile 6 – Fluvic Phaeozem | | | | | | | | | | |
| Ah1 | 0–25 | 9.79 | 5.99 | 3.84 | 2.16 | 0.61 | 0.36 | 22.77 | 1.91 | 0.08 |
| Ah2 | 25–65 | 8.02 | 2.88 | 1.63 | 1.26 | 0.36 | 0.44 | 23.35 | 2.18 | 0.09 |
| A/Cg | 65–94 | 3.73 | 0.45 | 0.35 | 0.10 | 0.12 | 0.22 | 14.91 | 0.30 | 0.02 |
| Cr | 94–150 | 3.43 | 0.24 | 0.16 | 0.08 | 0.07 | 0.35 | 13.08 | 0.05 | 0.00 |
| Profile 7 – Fluvic Phaeozem | | | | | | | | | | |
| Ah1 | 0–20 | 11.89 | 9.17 | 5.51 | 3.66 | 0.77 | 0.40 | 23.66 | 1.99 | 0.08 |
| Ah2 | 20–53 | 8.91 | 2.36 | 1.45 | 0.91 | 0.27 | 0.39 | 24.77 | 1.90 | 0.08 |
| Cg1 | 53–68 | 4.58 | 1.22 | 0.69 | 0.53 | 0.27 | 0.44 | 14.40 | 0.26 | 0.02 |
| Cg2 | 68–82 | 7.14 | 2.83 | 1.67 | 1.17 | 0.40 | 0.41 | 13.47 | 0.14 | 0.01 |
| Cr | 82–150 | 5.00 | 0.65 | 0.46 | 0.19 | 0.13 | 0.29 | 12.08 | 0.09 | 0.01 |

**Table 5**
Sorptive characteristics of the studied soils

| Horizon | Depth [cm] | $Na^+$ | $K^+$ | $Ca^{2+}$ | $Mg^{2+}$ | TEB | $H_w$ | $Al_w$ | CEC | BS |
|---|---|---|---|---|---|---|---|---|---|---|
| | | $cmol_{(+)}\ kg^{-1}$ | | | | | | | | % |
| Profile 1 – Eutric Gleyic Fluvisol | | | | | | | | | | |
| Ah | 0–13 | 0.19 | 0.12 | 1.46 | 0.68 | 2.45 | 3.03 | 1.54 | 5.48 | 44.7 |
| Cg1 | 13–43 | 0.19 | 0.06 | 2.30 | 0.74 | 3.29 | 0.31 | 0.11 | 3.60 | 91.4 |
| Cg2 | 43–49 | 0.17 | 0.10 | 3.66 | 0.73 | 4.66 | 0.29 | 0.10 | 4.95 | 94.0 |
| Cg3 | 49–65 | 0.14 | 0.03 | 1.61 | 0.49 | 2.28 | 0.11 | 0.03 | 2.39 | 95.3 |
| Cr1 | 65–68 | 0.15 | 0.02 | 1.74 | 0.56 | 2.47 | 0.27 | 0.12 | 2.73 | 90.2 |
| Cr2 | 68–70 | 0.18 | 0.11 | 4.72 | 0.79 | 5.80 | 0.09 | 0.02 | 5.89 | 98.5 |
| Cr3 | 70–79 | 0.16 | 0.03 | 2.17 | 0.60 | 2.96 | 0.07 | 0.02 | 3.03 | 97.8 |
| Cr4 | 79–83 | 0.25 | 0.14 | 7.53 | 0.97 | 8.88 | 0.08 | 0.02 | 8.96 | 99.1 |
| Cr5 | 83–150 | 0.17 | 0.02 | 1.83 | 0.61 | 2.64 | 0.06 | 0.02 | 2.70 | 97.9 |
| Profile 2 – Fluvic Gleyic Mollic Umbrisol | | | | | | | | | | |
| Ah1 | 0–22 | 0.13 | 0.06 | 2.05 | 0.61 | 2.85 | 3.63 | 1.90 | 6.48 | 44.0 |
| Ah2 | 22–30 | 0.16 | 0.03 | 4.15 | 0.78 | 5.12 | 1.08 | 0.54 | 6.20 | 82.6 |
| Ah3 | 30–41 | 0.22 | 0.02 | 8.55 | 0.97 | 9.76 | 0.39 | 0.15 | 10.14 | 96.2 |
| C | 41–70 | 0.18 | 0.02 | 2.17 | 0.62 | 2.99 | 0.11 | 0.03 | 3.10 | 96.6 |
| Cr1 | 70–80 | 0.14 | 0.02 | 1.50 | 0.51 | 2.18 | 0.69 | 0.32 | 2.86 | 76.0 |
| Cr2 | 80–83 | 0.22 | 0.08 | 4.98 | 0.80 | 6.08 | 0.06 | 0.02 | 6.14 | 99.0 |
| Cr3 | 83–150 | 0.13 | 0.01 | 1.71 | 0.56 | 2.42 | 1.06 | 0.49 | 3.48 | 69.5 |
| Profile 3 – Fluvic Gleyic Phaeozem | | | | | | | | | | |
| Ah | 0–24 | 0.17 | 0.03 | 3.84 | 0.71 | 4.74 | 0.29 | 0.12 | 5.03 | 94.2 |
| C | 24–60 | 0.17 | 0.02 | 4.49 | 0.70 | 5.38 | 0.22 | 0.09 | 5.60 | 96.0 |
| Cr | 60–150 | 0.15 | 0.03 | 1.71 | 0.49 | 2.38 | 0.11 | 0.03 | 2.49 | 95.6 |
| Profile 4 – Fluvic Gleyic Mollic Umbrisol | | | | | | | | | | |
| Ah1 | 0–15 | 0.17 | 0.06 | 2.00 | 0.73 | 2.96 | 3.10 | 1.43 | 6.06 | 48.8 |
| Ah2 | 15–39 | 0.16 | 0.04 | 2.95 | 0.73 | 3.88 | 0.50 | 0.24 | 4.38 | 88.6 |
| Ah3 | 39–51 | 0.19 | 0.03 | 12.18 | 1.08 | 13.48 | 0.26 | 0.07 | 13.74 | 98.1 |
| AC | 51–60 | 0.18 | 0.03 | 6.30 | 0.86 | 7.37 | 0.12 | 0.04 | 7.49 | 98.3 |
| Cr | 60–150 | 0.18 | 0.05 | 2.35 | 0.73 | 3.31 | 0.06 | 0.02 | 3.37 | 98.2 |
| Profile 5 – Fluvic Phaeozem | | | | | | | | | | |
| Ah | 0–40 | 0.20 | 0.06 | 5.98 | 0.94 | 7.18 | 2.32 | 1.22 | 9.50 | 75.6 |
| C | 40–53 | 0.13 | 0.02 | 2.01 | 0.47 | 2.63 | 0.25 | 0.09 | 2.88 | 91.5 |
| A1 | 53–70 | 0.15 | 0.05 | 6.02 | 0.57 | 6.79 | 0.11 | 0.03 | 6.89 | 98.4 |
| A2 | 70–88 | 0.20 | 0.06 | 7.96 | 0.71 | 8.93 | 0.11 | 0.03 | 9.04 | 98.7 |
| Cg | 88–100 | 0.15 | 0.02 | 1.62 | 0.47 | 2.26 | 0.11 | 0.03 | 2.36 | 95.5 |
| Cr | 100–150 | 0.15 | 0.02 | 1.87 | 0.49 | 2.53 | 0.05 | 0.02 | 2.58 | 97.9 |
| Profile 6 – Fluvic Phaeozem | | | | | | | | | | |
| Ah1 | 0–25 | 0.18 | 0.09 | 4.64 | 0.86 | 5.77 | 2.12 | 0.96 | 7.88 | 73.2 |
| Ah2 | 25–65 | 0.20 | 0.04 | 16.78 | 1.42 | 18.44 | 0.18 | 0.04 | 18.62 | 99.0 |
| A/Cg | 65–94 | 0.15 | 0.04 | 5.83 | 0.72 | 6.74 | 0.10 | 0.03 | 6.84 | 98.5 |
| Cr | 94–150 | 0.11 | 0.03 | 1.18 | 0.39 | 1.72 | 0.05 | 0.01 | 1.77 | 97.3 |
| Profile 7 – Fluvic Phaeozem | | | | | | | | | | |
| Ah1 | 0–20 | 0.25 | 0.13 | 2.46 | 0.91 | 3.75 | 3.35 | 1.82 | 7.10 | 52.9 |
| Ah2 | 20–53 | 0.22 | 0.10 | 6.11 | 1.02 | 7.44 | 0.50 | 0.23 | 7.95 | 93.7 |
| Cg1 | 53–68 | 0.12 | 0.03 | 1.70 | 0.48 | 2.34 | 0.21 | 0.06 | 2.55 | 91.7 |
| Cg2 | 68–82 | 0.14 | 0.02 | 1.29 | 0.47 | 1.92 | 0.17 | 0.07 | 2.09 | 91.8 |
| Cr | 82–150 | 0.15 | 0.01 | 0.93 | 0.38 | 1.47 | 0.11 | 0.03 | 1.58 | 93.2 |

### 3.5. Sorptive properties

The CEC of the soils varied between 1.58 and 18.62 cmol$_{(+)}$ kg$^{-1}$ (Table 5). It varied considerably between locations and soil horizons, reaching its maximum values in the A horizons and minimum values in the C horizons. Typically, the CEC showed a positive correlation with the clay ($R^2 = 0.624$) and TOC ($R^2 = 0.804$) contents, as well as the GSO ($R^2 = 0.591$). Basic cations predominated in the soil sorption complex, as evidenced by a BS>90% in most cases. This value only fell below 50% in the topsoil of profiles 1, 2, and 4. $Ca^{2+}$ constituted a major basic cation in all the soils, followed by $Mg^{2+}$ and $K^+$. The $Na^+$ content was very low, rarely exceeding 0.2 cmol$_{(+)}$ kg$^{-1}$.

## 4. Discussion

Detailed studies performed in the valley of the Leśna stream (Jonczak, 2015), located approximately 35 km north-west from the Kamienna stream, have highlighted that headwater stream valleys are specific soil-forming environments. In the region of Middle Pomerania, the valleys are usually deeply incised into the surficial deposits and are characterized by steep slopes and large river water-table gradients. These factors promote rapid surface runoff, especially in catchments developed on fine-grained sediments and/or during winter and early spring, when the soil surface is frozen (Florek et al., 2009). Rapid floods accelerate erosion of the slopes and marginal parts of the plateau and the accumulation of eroded materials (colluvial and alluvial) in the valley bottom. Consequently, poorly developed (eroded) soils commonly occur on the slopes, whereas Fluvisols and various other soil types developed from alluvial and colluvial materials fill the valley bottom. Jonczak (2015) suggested that, in such valleys during the Holocene, episodes of extremely strong floods could occur, that resulted in the total erosion of the soils in the valley bottom, following by the accumulation of a new series of alluvial sediments. This hypothesis has found supported from radiocarbon and thermoluminescence dating of the soils, as well as chemical indicators of weathering and pedogenesis. The presence of well-developed spring niches along the slope feet is another feature of the headwater river valleys in the studied area. Histosols and Gleysols are typical soils in the spring locations (Jonczak and Cysewska, 2010; Jonczak et al., 2015). While some of the abovementioned features apply to the Kamienna stream valley, the occurrence and importance of strong floods have not yet been confirmed there. Due to the dominance of sandy (permeable) sediments in the catchment, however, there is likely much less flooding than in the Leśna and Jarosławianka valleys.

The soils developed from *fluvic* materials in the Kamienna stream valley showed great variability in terms of their morphology and certain characteristics, which was reflected in their classification. The presence of Eutric Gleyic Fluvisols, Fluvic Gleyic Mollic Umbrisols, Fluvic Gleyic Phaeozems and Fluvic Phaeozems highlights SOM accumulation and gleying as major soil-forming processes, accompanied by a high trophic status due to the influence of river water. The features observed in this study have been commonly reported for Fluvisols and related soils (e.g., Rytelewski, 1965; Chojnicki, 2004; Kabała et al., 2011). Stratification of the A horizons in the studied soils could indicate their natural character as well as the origin of some of the SOM from external sources. Headwater bogs in the upper and middle courses of the stream should be noted as potential sources of that component.

The textural parameters of alluvial materials can well reflect the past dynamics of fluvial processes (Szmańda, 2010), and there is a general increase in the content of fine particles in the sediments along rivers. The studied soils represented mostly sandy textural groups, and they were enriched in gravel. Thus indicates a highly dynamic fluvial environment during sedimentation. Based on the Folk and Ward (1957) textural measures (Table 2, Fig. 2) and CM Passega diagram (Passega, 1964, Fig. 3), it can be estimated that saltation and rolling were the major mechanisms of sediment transport. The spatial distribution of textural parameters along the valley highlighted the importance of local-scale factors, such as outflows from headwater niches. In addition, coarse wood debris in a stream can strongly modify the water flow dynamics and erosion/sedimentation (Malik, 2004). The role of local-scale factors was clearly demonstrated in this study by profiles 1–4. Although the distance between these was only a few dozen meters, they exhibited a considerable differences in textural fraction contents, including gravel.

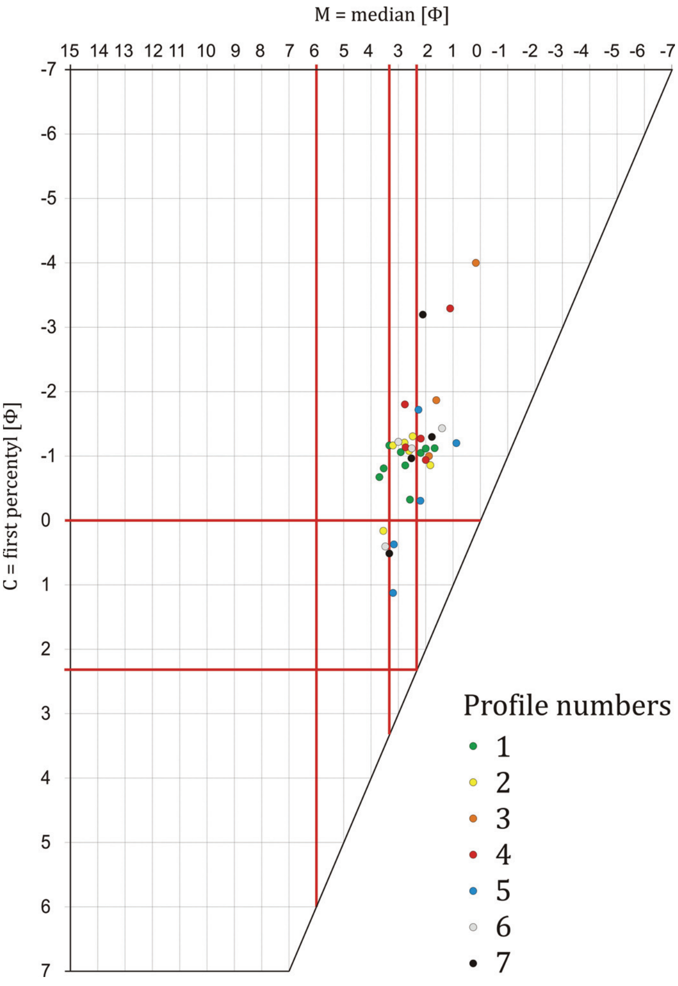

**Fig. 3.** CM Passega diagram

Generally, admixtures of fractions > 2.0 mm in alluvial soils is low in lowland river valleys, whereas in this study, this fraction amounted up to 64.1%. A greater importance of local-scale factors over general mechanisms of downstream fluvial transport was also reflected in the variability of the GSS and GSO (Fig. 2). These values showed no clear tendencies along the stream, with only the roundness of the 0.6–0.8 mm grains tending to increase downstream. Poorly rounded grains predominated in all horizons, with the contribution of well-rounded grains never exceeding 9.3%.

Large differences in textural parameters and SOM content were reflected in the physical characteristics of the studied soils. Based on the Ad-hoc-AG-Boden (2005) descriptions, the A horizons were very loose and had granular structure. These features are typical of humus-rich, biologically active soils. The bulk density of the studied soils confirmed good ecological condition and their natural character. In arable Fluvisols, the bulk density is usually higher (Niedźwiecki et al., 2010) due to tillage effect. The bulk density of the deeper horizons varied strongly, mainly reflecting the textural characteristics of the mineral substrates. The SOM content and particle size distribution were also major factors influencing the specific surface area, which was generally low in the C horizons and much higher in the humus-rich A horizons. The relationships determined in this study have been reported previously by several authors (e.g., De Kimpe et al., 1979; Dąbkowska-Naskręt, 1990). Additionally, Dąbkowska-Naskręt (1996) claimed that free Fe oxides can strongly influence the specific surface area of Fluvisols. However, their role in the soils of the Kamienna stream valley was beyond the remit of this study.

Due to the influence of river water, the pH values of river valley soils are often close to neutral (Dąbkowska-Naskręt, 1990; Czarnowska et al., 1995; Chojnicki, 2002; Kacprzak et al. 2012). In most of the studied soils, the pH was acidic or strongly acidic, with a general increasing tendency with depth (Table 1). Acidic soils have also been reported from the valleys of the Leśna (Jonczak, 2015) and Jarosławianka (Jonczak and Kowalkowski, 2013) streams. Their low pH values have been explained by there being a predominance of strongly acidic soils in the catchment in tandem with concentrations of coniferous forests. Acidic topsoils can indicate a limited groundwater effect. The factors described above may also have influenced the pH of the soils in the Kamienna stream valley. Additionally, soil pH can be influenced by the acidic Histosols that occur in spring niches (Jonczak et al., 2016), which may provide an external source of SOM. Strzemski (1955) reported, that in the soils of the Niemen and Prypeć rivers valleys, external sources of SOM were more important than *in-situ* humification.

The cumulative effects of supplies of SOM from external sources, accompanied by humification and riparian vegetation, contributed to substantial stocks of SOM in the studied soils. They were also rich in N, as evidenced by their low C:N ratios, in most cases (Table 3). The presence of appreciable amounts of TOC and N throughout the profiles is an inherent feature of *fluvic* materials (Classification of the soils of Poland, 6th Edition, 2019). The TOC and N contents, along with other elements, in headwater catchments must be considered in the context of the one-way flow of water and its role as a carrier of solutes and suspensions. Jonczak (2015) demonstrated higher stocks of TOC and N in the soils in valley bottoms as opposed to the slopes and plateaus. P showed the opposite tendency, with the studied soils generally being poor in that element, although its content varied among the locations and horizons (Table 3). A low P content in forest soils is typical because it is an element required for plant growth, being strongly taken up by roots and translocated from leaves to shoots during autumn. The intensity of that process is high even at relatively rich sites (Dziadowiec et al., 2007). Research performed by Jonczak et al. (2016) in the valley of the Kamienna stream showed that black alder litterfall is poor in P, K, and Ca. The contents of K, Ca, and Mg in soils are more strongly affected by the mineral components than by the SOM. Generally, these elements occurred in lower amounts in the studied soils than in soils reported on the literature (e.g., Malinowski et al., 2004), although they occurred in similar amounts to those found in Fluvisols in the Leśna stream valley (Jonczak, 2015). The low Ca contents were due to the sandy texture of the soils in this study. As a major component of aluminosilicates, positively correlates with the clay fraction. It is also commonly present in the form of carbonate, which was not present in the studied soils.

The various forms of Fe (total, free, amorphous, crystalline, and silicate) have been commonly used as measures of weathering and pedogenesis (e.g., Konecka-Betley, 1968; Chojnicki, 2004; Degórski et al., 2013). The total Fe content strongly varies among soils, mainly reflecting the origin and mineralogy of the parent material (Brożek and Zwydak, 2010; Lu et al., 2017), and it is usually positively correlated with the clay fraction (Jonczak, 2015). The studied Fluvisols were poor in this element, especially when compared with the clay-rich Fluvisols studied by Dąbkowska-Naskręt (1990), Czarnowska et al. (1995), and Chojnicki (2004). The values of $Fe_d/Fe_t$ ratios varied strongly among the soil profiles and with depth (Table 4), usually being recorded the highest in the A horizons, especially in the topsoil. The $Fe_d/Fe_t$ ratio is commonly used measure of weathering intensity. However, it cannot be used directly in this context for Fluvisols because the accumulation of sesquioxides in these soils arises not only from *in-situ* weathering, but also from crystallization from groundwater (Konecka-Betley, 1968; Laskowski and Szozda, 1985). The observed predominance of amorphous Fe over its crystalline form is typical of Fluvisols due to their high moisture content (Stonehouse and Arnaud 1971). In addition, the studied soils were rich in SOM, component that inhibits crystallization of free oxides (Cornell and Schwertmann, 1979). This relationship was confirmed by the positive correlation between $Fe_o$ and TOC.

The sandy texture of the studied soils was reflected in the generally low CEC values, which were usually the highest in the humus-rich A horizons. A positive correlation with TOC highlighted the importance of SOM as a factor in soil sorption. Generally, the CEC in soils is directly affected by the specific surface area (Evans, 1982; Dąbkowska-Naskręt, 1990), and this was confirmed in this study ($R^2$ = 0643). The predominance of basic cations in the soil sorption complex is typical of river valley soils (Rytelewski, 1965; Czarnowska et al., 1995; Pisarek and Żarczyńska, 2002).

## 5. Conclusions

The results of this study enabled characterization of the soil-forming processes and their development along with certain properties of the soils that developed from the alluvial sediments that cover the valley bottom of the Kamienna stream. In addition, some features specific to the soils having arising from the headwaters of the valley were identified. A strong predominance of coarse textural fractions (sand with admixtures of gravel) indicated the accumulation of alluvial sediments in a highly dynamic fluvial environment, whereas stratification reflected a temporal variability in that environment. In turn, the spatial distribution of the textural characteristics highlighted the greater role of local-scale factors over general mechanisms of downstream fluvial transport in characteristics such as soil heterogeneity. The accumulation of SOM and the gleying due to groundwater were identified as major soil-forming processes in the studied soils. Their roles were reflected in the classification of the soils – Eutric Gleyic Fluvisols, Fluvic Gleyic Mollic Umbrisols, Fluvic Gleyic Phaeozems and Fluvic Phaeozems. Deep A horizons with high SOM contents proved conditions were favorable for humification, which is typical of riparian areas. However, the stratification of these horizons indicated the partially allochthonous origin of the SOM. While headwater bogs in the upper and middle courses of the stream should be considered as potential sources of the SOM, their importance could not be precisely estimated based on the data obtained. The origin of parent material, the sandy texture, SOM, and groundwater were the major factors that influenced most of the characteristics of the studied soils. The soil physical properties confirmed their good ecological condition, indicating significant biological activity. Additionally, the soils were rich in N, while being poor in P, K, Ca, and Mg. These features correspond to the soils of headwater niches, the subject of earlier studies on the Kamienna stream valley. The soils were also poor in Fe and Al. Generally, low sesquioxides content indicate poorly advanced weathering, whereas the predominance of their amorphous forms over the crystalline forms is a function of high moisture and SOM contents. The soils were also characterized by low CEC values, and the base saturation was very high in most horizons.

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# Procesy glebotwórcze i właściwości gleb wykształconych z materiałów typu *fluvic* w dolinach źródliskowych Pomorza Środkowego – studium przypadku strumienia Kamienna

## Słowa kluczowe

Obszary źródliskowe
Procesy fluwialne
Powstawanie gleb
Doliny rzeczne
Właściwości gleb

## Streszczenie

Celem badań była charakterystyka procesów glebotwórczych i wybranych właściwości gleb wykształconych z osadów aluwialnych w dolinie strumienia Kamienna, reprezentującego typową dla obszaru Pomorza Środkowego głęboko wciętą w glacjalne i fluwioglacjale osady dolinę źródliskową. Badaniami objęto siedem profili glebowych usytuowanych wzdłuż strumienia. Gleby zostały opisane, opróbowane i przeanalizowane stosując standardowe dla badań gleboznawczych metody. Materiały macierzyste badanych gleb wykazywały warstwowanie i miały uziarnienie piasków, w niektórych poziomach ze znacznymi domieszkami frakcji żwirowej. Wskaźniki teksturalne wskazują na ich akumulację w środowisku fluwialnym o wysokiej dynamice. Gleby wykazywały dużą zmienność przestrzenną, podkreślając znaczenie czynników o charakterze lokalnym. Głównymi procesami glebotwórczymi była akumulacja materii organicznej i oglejenie gruntowe, co znajduje odzwierciedlenie w klasyfikacji gleb – Eutric Gleyic Fluvisols, Fluvic Gleyic Mollic Umbrisols, Fluvic Gleyic Phaeozems i Fluvic Phaeozems. Gleby charakteryzowały się głębokimi poziomami A i wysoką zawartością materii organicznej. Warstwowanie poziomów próchnicznych może dowodzić jej częściowo allochtonicznego charakteru, a występujące w górnym i środkowym biegu strumienia nisze źródliskowe są prawdopodobnie zewnętrznym źródłem tego składnika. Właściwości fizyczne badanych gleb wskazują na ich dobrą kondycję ekologiczną. Ponadto, gleby były bogate w N przy niskiej zasobności w P, K, Ca, Mg, Fe i Al. Generalnie mała zawartość żelaza wolnego wskazuje na słabe zaawansowanie procesów wietrzenia. Z kolei przewaga żelaza amorficznego nad krystalicznym jest efektem dużego uwilgotnienia i wysokiej zasobności w materię organiczną. Ponadto, gleby charakteryzowały się małą kationową pojemnością sorpcyjną, która wykazywała zróżnicowanie w zależności od zawartości materii organicznej i iłu. Gleby generalnie miały kwaśny odczyn, a ich pH–$H_2O$ wahało się w większości przypadków w granicach 5,0–7,0. Relatywnie niskie wartości pH nie znalazły jednak odzwierciedlenia w wysokim wysyceniu kompleksu sorpcyjnego kationami kwasowymi.