



Dijlah Journal of Agricultural Sciences

Journal homepage: <https://djas.uowasit.edu.iq/index.php/djas/en>



Research article

Topographic Controls on Soil Formation and Development in the Lake Habbaniyah Basin: A Morphometric and Pedological Investigation.

Saleh Abid Saleh

Ministry of Education, Directorate of Vocational Education, Al-Anbar, Iraq

ARTICLE INFO

Keywords:

Lake Habbaniyah Basin;
Topographic control;
Morphometric analysis;
Pedogenic processes; Soil
formation;
Soil development;
Soil classification;
Aridisols; Calcids;
Gypsisols.

Article history:

Received: 30 Jun 2026
Accepted: 17 Sep 2026
Online: 30 Sep 2026

ABSTRACT

This study assessed the effect of topographic control on soil formation and development in the Lake Habbaniyah Basin using an integrated morphometric and pedological approach, and examined the relationship between land-surface features and the pedogenic processes controlling horizon formation and soil development. Basin morphometry was analyzed and three pedons were selected from contrasting topographic positions (upper, middle and lower slope). Standard laboratory procedures were used for morphological description, physical and chemical analysis, diagnostic-horizon identification, and classification according to the USDA Soil Taxonomy. The basin showed marked diversity in elevation, slope and drainage, strongly influencing soil distribution and development. Horizon thickness, differentiation and structural development varied clearly among the pedons with topographic position. Physical analyses showed a gradual decrease in sand and increase in silt and clay toward the lower positions due to transport and deposition, while chemical analyses showed neutral-to-slightly-alkaline reaction with a progressive increase in electrical conductivity, calcium carbonate, gypsum and salinity indices toward the lower positions. Calcification, gypsification and salinization, together with erosion and deposition, were the primary pedogenic processes, and their severity was strongly linked to the topographic gradient. The lower-basin pedon showed the greatest pedogenic development, the middle-slope pedon was intermediate, and the upper-slope pedon was least developed. All soils were classified as Aridisols, with the upper pedon in the Calcids suborder and the middle and lower pedons in the Gypsisols suborder. The study concludes that topography is the main factor controlling soil formation and development in the Lake Habbaniyah Basin, through its effect on water movement, sediment redistribution, salt accumulation, the intensity of pedogenic processes, and the formation of diagnostic horizons, and hence on the degree of soil development and classification. These supports combining morphometric analysis with pedological study for assessing soil resources and planning sustainable land management.

1. Introduction

Soil is one of the most important natural resources supporting agricultural and environmental activity, formed where the lithosphere, hydrosphere, atmosphere and biosphere interact over long periods to produce bodies that differ in physical, chemical, mineralogical and morphological properties. Soil formation is controlled by the factors outlined by Jenny (Abu Sufyah, 2007). climate, organisms, parent material, topography and time, acting

✉ *Corresponding author:
salehlaberi83@gmail.com (Saleh Abid Saleh)

separately or together to control soil qualities and degree of development (Abu Sufyah, 2007; Al-Bina & Al-Hadithi, 2011). Topography is one of the most important factors controlling soil formation in arid and semi-arid environments, since it directly governs surface- and ground-water distribution, slope gradient and orientation, erosion and deposition, and local variation in moisture and temperature. This is reflected in the varying dominance of calcification, gypsification, salinization and translocation of fine material, producing marked differences in horizon thickness and differentiation, physical and chemical properties, and consequently soil classification and degree of development (Al-Hadithi & Al-Bina, 2014; Al-Rawi & Khalaf Allah, 2000; Al-Samarrai, 2010). Morphometric study of drainage basins is a well-established technique for explaining the relationship between topographic features and the geomorphic processes controlling soil formation. Indices such as basin area, shape, drainage density, stream order, circularity ratio, elongation ratio, relief and slope are closely related to soil distribution and degree of development, and provide quantitative information on runoff dynamics, drainage efficiency, erosion intensity and depositional zones (Al-Zubaidi, 2012; Birkeland, 1999; Bockheim et al., 2014).

The Lake Habbaniyah Basin, one of the important basins of central Iraq, is characterized by diverse topographic and depositional units such as river terraces, floodplains, lacustrine sediments and valley-fill deposits, within an arid to semi-arid environment of low rainfall and high evaporation that favors accumulation of calcium carbonate, gypsum and soluble salts. Its diversity in elevation, slope and drainage network produces varying erosion and deposition rates, manifested in spatial variation of soil properties and degree of development (Brady & Weil, 2017; Buol et al., 2011; Dent & Young, 1981; Hillel, 2004). In recent decades, remote sensing, GIS and Digital Elevation Models have greatly advanced the study of drainage basins and their morphometric characteristics, allowing rapid, precise extraction of terrain indices linked to pedological characteristics. These techniques have deepened understanding of the spatial links between topography and pedogenic processes and have become essential tools in soil survey, classification and land-suitability evaluation (Iraqi Meteorological Organization and Seismology, 2024; Jenny, 1994).

This study aims to understand the effect of topographic control on soil formation and development in the Lake Habbaniyah Basin by combining basin morphometric analysis with field and laboratory investigation of soil profiles, in order to interpret the relationship between land-surface features and dominant pedogenic processes, identify diagnostic horizons, classify the soils, and evaluate their degree of development. The findings aim to provide a scientific basis for land-resource management, agricultural planning and rational land use in the study area.

2. Materials and Methods

2.1 Study Area

The study area lies in the Lake Habbaniyah Basin, Al-Anbar Governorate, western Iraq, between the Euphrates River and the lake, and shows marked variation in topographic units and slope gradients, including low-lying land adjacent to the lake, river terraces, hillslopes and higher surrounding ground. The climate is arid to semi-arid, with hot summers, low annual rainfall and high evaporation, directly influencing the dominant pedogenic processes and soil qualities.

2.2 Morphometric Analysis of the Basin

The morphometric investigation was carried out using GIS and remote-sensing techniques based on a Digital Elevation Model (DEM) to derive the basin's topographic characteristics. ArcGIS Pro (or ArcGIS 10.8) and hydrological analysis tools were used to delineate the basin boundary, extract the drainage network and organize the stream network following Strahler (Strahler, 1964).

A set of morphometric indices was extracted, including:

Basin area (A), Basin perimeter (P), Basin length (Lb), Circularity ratio, Elongation ratio, Form factor, Drainage density, Stream frequency, Relief ratio, Slope, Elevation, Slope aspect.

These indices were used to interpret the influence of topography on soil distribution, degree of development and dominant pedogenic processes.

2.3 Selection of Pedon Sites

Sites were selected based on the morphometric study and the basin's topographic variation. Three pedons representing the major topographic positions were excavated to reflect the influence of topography on soil formation and development:

- Pedon 1 (P1): located on the upper slope of the basin, representing steep terrain dominated by erosion and weak accumulation of fine material.
- Pedon 2 (P2): located on the middle slope, representing a transitional zone in which erosion and deposition are relatively balanced.
- Pedon 3 (P3): located in the lower, low-lying land near Lake Habbaniyah, where deposition and the accumulation of salts, gypsum and calcium carbonate increase.

The coordinates of the pedon sites were determined using a Global Positioning System (GPS) receiver.

2.4 Morphological Description

Where practicable, pedons were excavated to the parent material or to depths exceeding 150 cm, and field profiles were described according to the Soil Survey Manual (Soil Science Division Staff, 2017) and the Guidelines for Soil Description (Food and Agriculture Organization of the United Nations [FAO], 2006).

2.5 Sample Collection

Representative samples were taken from all genetic horizons of each pedon, air-dried, crushed and sieved through a 2-mm mesh for laboratory analysis.

2.6 Physical Analyses

Particle-size distribution by the hydrometer method, Bulk density, Particle density, Total porosity, Moisture content, Saturated hydraulic conductivity, Aggregate stability, where required.

2.7 Chemical Analyses

Soil reaction (pH), Electrical conductivity (EC), Calcium carbonate equivalent (CaCO_3), Gypsum content, Organic matter, Cation exchange capacity (CEC), Soluble cations (Ca^{2+} , Mg^{2+} , Na^+ , K^+), Soluble anions (Cl^- , SO_4^{2-} , HCO_3^- , CO_3^{2-}), Sodium adsorption ratio (SAR), and Exchangeable sodium percentage (ESP), where required.

2.8 Identification of Pedogenic Processes

Pedogenic processes were interpreted by integrating the morphological, physical and chemical properties of the soils to identify the dominant processes, including:

1. Calcification.
2. Gypsification.
3. Salinization.
4. Desalinization, where present.

5. Deposition and removal of material.
6. Surface erosion.
7. Translocation of fine material (lessivage), where present.

2.9 Determination of Diagnostic Horizons

Diagnostic horizons and features were determined from field and laboratory data according to USDA classification standards, including the Ochric epipedon, Calcic horizon and Gypsic horizon.

2.10 Soil Classification

Soils were classified to the family level, where data allowed, based on morphological description, physical and chemical analysis and diagnostic horizons, according to the latest USDA Soil Taxonomy.

2.11 Evaluation of Soil Development

The degree of soil development was evaluated by comparing horizon differentiation, horizon thickness, intensity of pedogenic processes, and carbonate, gypsum and salt content, together with topographic position and basin morphometric indices, to interpret the role of topography in soil formation and development.

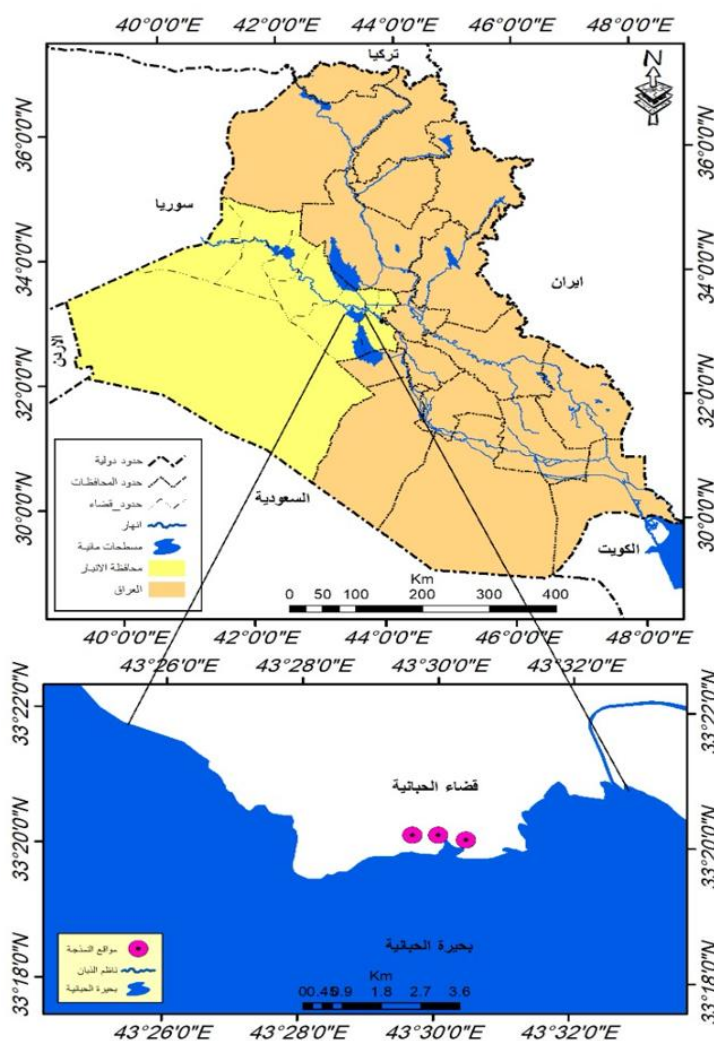


Figure 1. Location of the studied pedons within the study area.

3. Results and Discussion

3.1 Morphometric Analysis of the Lake Habbaniyah Basin

Morphometric analysis is an important quantitative method for studying drainage-basin characteristics, allowing interpretation of the relation between terrain characteristics, drainage network and geomorphic processes influencing soil formation. This study used DEM and GIS techniques to extract morphometric attributes of the basin and evaluate the effect of topography on pedogenic processes and soil quality. The study computed areal, form and relief features along with drainage-network characteristics, which are basic parameters for interpreting runoff rates, erosion intensity, depositional zones and the extent of soil development in the basin.

Areal and shape characteristics of the basin

The circularity ratio (0.46) and elongation ratio (0.71) indicate an elongated basin shape, which varies the travel time of surface runoff, decreasing flash-flood risk and increasing the spatial variability of erosion and deposition, reflected in differing soil properties between higher and lower sites.

Table 1. General morphometric characteristics of the Lake Habbaniyah Basin.

Parameter	Symbol	Value
Basin area (km ²)	A	515.8
Basin perimeter (km)	P	118.6
Basin length (km)	Lb	36.4
Maximum basin width (km)	W	20.8
Circularity ratio	Rc	0.46
Elongation ratio	Re	0.71
Form factor	Ff	0.39
Compactness coefficient	Cc	1.47

Drainage-network characteristics

The relatively low drainage density indicates high permeability of surface materials and lower surface runoff, allowing greater infiltration. The bifurcation ratio suggests the drainage network is regulated mainly by structural and topographic effects, with minimal geological influence on the drainage pattern.

Table 2. Drainage-network characteristics.

Parameter	Value
Highest stream order	5th order
Number of streams	287
Total stream length (km)	396.2
Drainage density (km/km ²)	0.77
Stream frequency	0.56
Length of overland flow	1.29 km
Mean bifurcation ratio	3.84

Relief characteristics

The basin shows moderate relief variation: erosion dominates in the higher areas, while the lower areas near Lake Habbaniyah are dominated by deposition, giving greater soil thickness and accumulation of fine material, calcium carbonate and gypsum.

Table 3. Relief characteristics of the basin.

Parameter	Value
-----------	-------

Maximum elevation (m)	167
Minimum elevation (m)	42
Relief (m)	125
Relief ratio	3.43
Mean slope (%)	5.8
Dominant slope class	Gentle to moderate

Distribution of pedon sites across the topographic units

Pedon distribution shows a clear topographic gradient reflected in soil qualities: Pedon 1 was strongly eroded with a shallow, weakly developed profile; Pedon 2 showed transitional characteristics; and Pedon 3 accumulated fine sediments, salts, gypsum and calcium carbonate due to reduced slope and slower flow, favoring clearer diagnostic layers and greater soil development.

The morphometric analysis indicates that topography is the dominant factor controlling the spatial variation of soil properties in the basin, with elevation, slope and drainage network driving erosion and deposition rates, and thus soil thickness, horizon development, carbonate/gypsum/salt distribution, and the resulting degree of pedogenic development and classification.

Table 4. Pedon locations relative to the topographic units.

Pedon	Topographic unit	Elevation (m)	Slope (%)	Position
P1	Upper slope	152	8.6	High
P2	Middle slope	103	4.1	Intermediate
P3	Lower land near the lake	49	1.3	Low

3.2 Morphological Properties

The morphological description of the three pedons showed a clear contrast in profile characteristics, mainly due to differing topographic positions and the resulting variation in slope, runoff, erosion and deposition, together with the arid to semi-arid climate and parent material. This was reflected in horizon thickness, color, texture, structure, and the degree of calcification, gypsification and salt accumulation, confirming topography as a governing factor in pedogenesis and degree of development.

Pedon 1 (P1) -upper slope

Pedon 1, on the upper slope, is dominated by erosion rather than deposition. Its genetic horizons are relatively shallow and weakly differentiated: a surface (Ap) horizon over a Bw horizon, a Bk horizon, and parent material (Ck) at depth. Surface colors were light brown, paling with depth as organic matter diminished and calcium carbonate accumulated - a gradation caused by low vegetation cover, high temperatures and enhanced aeration at this elevation. Soils ranged from loam to clay loam, with a granular surface structure grading to subangular blocky below, indicating incipient structural development that is nevertheless limited by ongoing erosion. Calcium carbonate accumulated markedly in the Bk horizon through capillary rise and evaporative precipitation, while gypsum accumulation was limited by the horizon's elevated position, which allows better drainage. These parameters indicate that this pedon is weakly to moderately developed, with erosion removing material faster than horizons can form.

Table 5. Morphological description of Pedon 1 (P1) — upper slope.

Horizon	Depth	Dry color	Moi st	Texture	Structure	Consistence	Porosity	Roots	CaCO ₃	Gypsum	Gravel (%)	Boundary
---------	-------	-----------	--------	---------	-----------	-------------	----------	-------	-------------------	--------	------------	----------

	(cm)			colo ur									
Ap	0-18	10YR 6/3	10YR 4/3	Sand y loam	Medium granular	Friable	Many	Ma ny	Few	None	5	Clear, wavy	
Bw	18-42	10YR 6/4	10YR 5/4	Loam	Medium subangul ar blocky	Slightly hard	Moder ate	Few	Moder ate	Trace	8	Gradu al	
Bk	42-86	10YR 7/4	10YR 5/4	Clay loam	Subangul ar blocky	Hard	Few	Rar e	Many	Few	12	Clear	
Ck	86-150 +	10YR 7/3	10YR 6/3	Sand y loam	Structure less	Relativel y hard	Few	Non e	Abund ant	Few	18	Parent materi al	

Pedon 2 (P2) - middle slope

Pedon 2, on the middle slope, is a transition zone where erosion and deposition are roughly balanced, shown by a thicker profile with five genetic strata, more distinct structure, and greater calcium carbonate and gypsum accumulation than Pedon 1. Colors ranged from brown to yellowish brown, indicating relatively good drainage and reduced organic matter, with texture shifting progressively to clay loam as fine particles carried from higher ground were deposited. Structure improved from granular at the surface to subangular blocky below, consistent with growing structural stability as clay and carbonate content increased. Distinct calcium carbonate accumulation and an incipient gypsic horizon (Bky) within the Bk horizon reflect active calcification and gypsification under high evaporation and limited leaching — the gypsic horizon itself marking more advanced development than Pedon 1. These results show that the middle-slope position favors accumulation of material translocated from higher elevations, giving greater horizon thickness and differentiation.

Table 6. Morphological description of Pedon 2 (P2) — middle slope.

Horiz	Depth (cm)	Dry color	Moist color	Texture	Structure	Consistency	Porosity	Roots	CaCO ₃	Gypsum	Gravimetric (%)	Bound
Ap	0-20	10YF	10YF	Silt loam	Granular	Friable	Many	Many	Few	None	2	Clear
Bw	20-41	10YF	10YF	Loam	Subangular blocky	Slightly hard	Moderate	Moderate	Moderate	Few	4	Gradual
Bk	48-91	10YF	10YR	Clay loam	Medium blocky	Hard	Moderate	Few	Many	Moderate	7	Clear
Bky	96-131	10YF	10YF	Clay loam	Coarse blocky	Hard	Few	Rare	Abundant	Many	9	Clear
C	140-180	10YF	10YR	Loam	Structure less	Hard	Few	None	Abundant	Moderate	12	Parent material

Pedon 3 (P3) - lower basin

Pedon 3, in the lower basin, is most affected by deposition of fine sediments carried by runoff, producing a markedly thicker profile with more strongly expressed horizons than the other two pedons. Surface horizons were relatively dark brown from organic matter and fine-particle deposition, while lower horizons paled with accumulating calcium carbonate, gypsum and soluble salts. The soil was silty clay to clay, with blocky and weakly prismatic structure at depth, suggesting shrink-swell behavior and salt/gypsum deposition. The greatest gypsum and calcium carbonate accumulation occurred in the subsurface horizons, with salt efflorescence and visible gypsum crystals resulting from low slope, poor internal drainage and high evaporation, which draw groundwater upward and precipitate salts, sulfates and carbonates. The presence of both gypsic and calcic horizons evidences the predominance of gypsification and calcification — key processes in arid environments — and, with the increased horizon thickness and structural development, marks this as the most pedogenically developed area of the basin. Overall, soil qualities changed gradually from the upper to the lower location: erosion dominated in Pedon 1 (shallow, weakly developed profile); Pedon 2 was transitional with erosion and deposition in balance; and Pedon 3 was clearly shaped by deposition and accumulation of fine material, salts, gypsum and calcium carbonate, with more clearly expressed horizons and greater development. These results confirm topography as the most important factor in soil formation in the basin, controlling surface-water distribution, drainage efficiency, erosion intensity and depositional zones, and hence the pedogenic processes, morphological variation and degree of development seen along the gradient from Pedon 1 (upper) through Pedon 2 (mid-slope) to Pedon 3 (lower).

Table 7. Morphological description of Pedon 3 (P3) — lower basin, near Lake Habbaniyah.

Horizon	Depth (cm)	Dry colour	Moist colour	Texture	Structure	Consistence	Porosity	Roots	CaCO ₃	Gypsum	Salt features	Boundary
Ap	0-18	10Y R	10Y R	Silty clay loam	Granular	Friable	Many	Many	Few	Few	None	Clear
Bk	18-55	10Y R	10Y R	Clay loam	Subangular blocky	Hard	Mode rate	Mode rate	Many	Mode rate	Trace	Gradual
By	55-95	10Y R	10Y R	Clay loam	Weak prismatic	Hard	Few	Few	Many	Abundant	Slight efflorescence	Clear
Byz	95-140	10Y R	10Y R	Silty clay	Coarse blocky	Very hard	Very few	Rare	Abundant	Very abundant	Clear salt efflorescence	Clear
Cy	140-160 +	10Y R	10Y R	Loam	Structureless	Hard	Few	None	Abundant	Abundant	Gypsum crystals	Parent material

3.3 Physical Properties

The physical analyses of the three pedons showed clear variation in particle-size distribution, bulk density, particle density, total porosity and moisture content, mainly reflecting differing topographic positions and the resulting variation in erosion, transport, deposition, parent material and dominant pedogenic processes.

Table 8. Physical properties of Pedon 1 (P1) — upper slope.

Horizon	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Texture	Bulk density (Mg m ⁻³)	Particle density (Mg m ⁻³)	Porosity (%)	Moisture content (%)
---------	------------	----------	----------	----------	---------	------------------------------------	--	--------------	----------------------

Ap	0-18	58	24	18	Sandy loam	1.39	2.64	47.3	8.2
Bw	18-42	49	28	23	Loam	1.43	2.65	46.0	9.4
Bk	42-86	41	30	29	Clay loam	1.48	2.66	44.4	10.6
Ck	86-150+	54	25	21	Sandy clay loam	1.52	2.66	42.9	9.1

Pedon 1 (P1) - upper slope

Sand was the dominant fraction in the surface horizons, decreasing with depth as silt and clay increased, because the upper-slope position promotes erosion and removal of fine particles, concentrating sand at the surface. Texture changed from sandy loam at the surface to clay loam at depth, reflecting the onset of downward fine-particle movement, though this process is limited by low rainfall. Bulk density was relatively low at the surface and rose with depth as organic matter and root abundance decreased and particle packing and carbonate accumulation increased, while particle density varied little given the near-constant mineral composition. Porosity decreased with depth as bulk density increased, and moisture content was very low due to the coarse texture, strong permeability and rapid drainage at this elevated site. These results suggest that the topographic setting favored erosion and poor moisture retention, constraining pedogenesis relative to the other sites.

Table 9. Physical properties of Pedon 2 (P2) — middle slope.

Horizon	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Texture	Bulk density (Mg m ⁻³)	Particle density (Mg m ⁻³)	Porosity (%)	Moisture content (%)
Ap	0-20	46	32	22	Loam	1.35	2.64	48.9	10.8
Bw	20-48	40	33	27	Clay loam	1.40	2.65	47.2	12.4
Bk	48-96	36	32	32	Clay loam	1.44	2.66	45.9	13.6
Bky	96-140	34	30	36	Clay	1.49	2.67	44.2	14.2
C	140-160+	42	31	27	Clay loam	1.50	2.67	43.8	12.1

Pedon 2 (P2) - middle slope

Sand content dropped and silt and clay rose compared with Pedon 1, indicating that the middle-slope site is a transitional zone receiving material from higher terrain as shown in table 10. This was reflected in texture shifting from loam to clay loam, giving greater water- and nutrient-holding capacity than Pedon 1. Bulk density increased somewhat with depth as organic matter decreased and clay and carbonates accumulated, while particle density remained within the typical range for arid-climate soils. Surface horizons had higher porosity, decreasing progressively with depth due to packing; moisture content was higher than Pedon 1 owing to increased clay content and water retention. These properties show that the mid-slope position provides more stable conditions for profile formation, due to the relative balance between removal and deposition, giving increased horizon thickness and improved physical properties.

Table 10. Physical properties of Pedon 3 (P3) — lower basin, near Lake Habbaniyah.

Horizon	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Texture	Bulk density (Mg m ⁻³)	Particle density (Mg m ⁻³)	Porosity (%)	Moisture content (%)
---------	------------	----------	----------	----------	---------	------------------------------------	--	--------------	----------------------

Ap	0-18	34	38	28	Silty clay loam	1.31	2.63	50.2	15.4
Bk	18-55	30	36	34	Clay loam	1.36	2.65	48.7	17.2
By	55-95	26	35	39	Clay	1.42	2.66	46.6	18.8
Byz	95-140	24	33	43	Clay	1.47	2.67	44.9	19.6
Cy	140-160	32	34	34	Clay loam	1.49	2.67	44.2	17.3

Pedon 3 (P3) - lower basin

Pedon 3 had the highest clay and silt and lowest sand of the three pedons, reflecting its position at the base of the basin where fine sediments carried by runoff settle out. This was evident in the dominance of silty clay loam and clay textures, which have high water-holding capacity. The lowest bulk density occurred at the surface, due to roots and organic matter, increasing gradually with depth from gypsum and calcium carbonate accumulation and natural compaction. Porosity was highest at the surface and decreased with depth, while moisture content increased markedly relative to Pedons 1 and 2 owing to higher clay content, lower slope and slower drainage. These results show that the lower topographic position favored deposition of fine particles, greater soil thickness and improved moisture retention, contributing to the formation of calcic and gypsic layers. Comparing the pedons shows a clear physical gradient from upper to lower positions: sand content dropped and silt and clay rose progressively from Pedon 1 to Pedon 3 due to transport and deposition of finer particles. Bulk density was lower at the surface in all pedons due to organic matter and roots, and increased with depth from packing and carbonate/gypsum accumulation, while particle density was similar across pedons given the dominance of silicate minerals and carbonates throughout. Porosity was inversely related to bulk density, decreasing with depth, while moisture content increased markedly from Pedon 1 to Pedon 3 with the shift from coarse to fine texture and reduced slope. These results confirm that topography was the dominant factor controlling physical-property variation in the basin: increased slope at higher sites promoted erosion and reduced clay content and moisture, while reduced slope at lower sites promoted deposition, higher water-holding capacity and more favorable pedogenic conditions.

3.4 Chemical Properties

The chemical analyses showed clear differences in pH, EC, organic matter, calcium carbonate, gypsum, CEC, soluble cations and anions, and sodicity indices (SAR and ESP) among the pedons, reflecting the effect of topographic position on water circulation, drainage and erosion/deposition, compounded by the arid to semi-arid climate limiting leaching and increasing salt, carbonate and gypsum buildup as shown in table 11, 12,13,14,15.

Table 11. Chemical properties of Pedon 1 (P1) — upper slope.

Horizon	Depth (cm)	pH	EC (dS m ⁻¹)	Organic matter (%)	CaCO ₃ (%)	Gypsum (%)	CEC (cmol(+)/kg)	SAR	ESP (%)
Ap	0-18	7.55	1.82	1.24	18.6	1.8	17.4	2.8	3.6
Bw	18-42	7.71	2.14	0.86	22.3	2.4	18.5	3.4	4.8
Bk	42-86	7.89	2.63	0.51	31.8	3.2	19.6	4.1	5.7
Ck	86-150+	8.03	2.95	0.27	35.9	3.8	18.9	4.5	6.2

Table 12. Chemical properties of Pedon 2 (P2) — middle slope.

Horizon	Depth (cm)	pH	EC (dS m ⁻¹)	Organic matter (%)	CaCO ₃ (%)	Gypsum (%)	CEC (cmol(+)/kg)	SAR	ESP (%)
Ap	0-20	7.48	2.21	1.42	15.8	2.3	20.8	3.6	4.9
Bw	20-48	7.66	2.85	0.98	21.5	3.6	22.6	4.5	6.4
Bk	48-96	7.86	3.64	0.63	29.7	5.8	24.2	5.8	8.1
Bky	96-140	8.04	4.46	0.34	35.8	8.6	25.5	7.1	10.2
C	140-160+	8.10	4.72	0.21	37.4	9.2	24.9	7.4	10.8

Table 13. Chemical properties of Pedon 3 (P3) — lower basin.

Horizon	Depth (cm)	pH	EC (dS m ⁻¹)	Organic matter (%)	CaCO ₃ (%)	Gypsum (%)	CEC (cmol(+)/kg)	SAR	ESP (%)
Ap	0-18	7.42	3.84	1.68	14.6	3.5	25.8	5.2	7.4
Bk	18-55	7.72	5.36	1.04	26.8	7.8	27.6	8.4	11.8
By	55-95	7.95	7.62	0.66	33.9	12.5	29.3	11.6	15.7
Byz	95-140	8.12	9.84	0.34	38.7	18.6	30.4	14.3	18.9
Cy	140-160+	8.18	10.62	0.18	40.6	21.3	29.8	15.2	20.1

Table 14. Soluble cations in the saturation-extract paste (mmolc L⁻¹).

Pedon	Horizon	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺
P1	Ap	8.2	4.1	3.2	0.42
P1	Bw	9.6	4.8	4.4	0.38
P1	Bk	11.8	5.9	5.8	0.35
P1	Ck	12.4	6.2	6.3	0.31
P2	Ap	10.4	5.6	5.2	0.46
P2	Bw	11.9	6.1	6.8	0.42
P2	Bk	13.8	7.2	8.5	0.39
P2	Bky	15.6	8.3	10.6	0.35
P2	C	16.1	8.8	11.2	0.33
P3	Ap	12.6	6.8	8.4	0.51
P3	Bk	15.7	8.2	12.4	0.46
P3	By	18.9	9.7	17.6	0.42
P3	Byz	21.6	10.9	22.8	0.38
P3	Cy	22.4	11.4	24.1	0.35

Table 15. Soluble anions in the saturation-extract paste (mmolc L⁻¹).

Pedon	Horizon	HCO ₃ ⁻	Cl ⁻	SO ₄ ²⁻
P1	Ap	2.8	3.4	9.7
P1	Bw	2.4	4.6	11.8
P1	Bk	2.1	5.8	14.4
P1	Ck	1.9	6.2	15.8
P2	Ap	3.1	5.2	12.6
P2	Bw	2.8	6.8	15.4
P2	Bk	2.5	8.6	18.9
P2	Bky	2.2	10.8	23.6
P2	C	2.0	11.2	24.8
P3	Ap	3.4	8.8	18.2
P3	Bk	3.0	12.6	24.4
P3	By	2.5	17.8	31.2
P3	Byz	2.2	23.6	38.8
P3	Cy	2.0	25.1	41.6

Soil reaction (pH)

pH ranged from 7.42 to 8.18, placing all soils in the neutral-to-slightly-alkaline range, with a modest increase with depth in all pedons attributed to increasing calcium carbonate and decreasing organic matter at depth. The highest pH values occurred in Pedon 3, linked to carbonate and salt accumulation from poor drainage and high evaporation, while Pedon 1 had the lowest values due to its elevated, better-drained position.

Electrical conductivity (EC)

Electrical conductivity increased from Pedon 1 to Pedon 3 and with depth, reflecting increasing buildup of soluble salts toward the lower areas. This gradient reflects topography: higher sites allow partial drainage of water and salts, while low-lying areas near the lake receive saline water that precipitates within the profile, particularly in the deeper horizons, under high evaporation. The high EC values in Pedon 3 reflect the predominance of salinization, one of the main pedogenic processes in dry and semi-arid environments.

Organic matter

Organic matter was concentrated in the surface horizons of all pedons and declined with depth, reflecting the concentration of roots and biological activity near the surface. The highest organic-matter content occurred in Pedon 3, due to greater soil moisture and finer texture favoring accumulation of plant residues.

Calcium carbonate (CaCO₃)

Calcium carbonate content rose progressively with depth in all pedons, with the highest values in the subsurface horizons of Pedon 3. This reflects the predominance of calcification: calcium-bearing solutions

precipitate as calcium carbonate on evaporation, forming well-expressed calcic horizons — a key pedogenic process in dry areas where leaching cannot remove carbonates.

Gypsum content

Gypsum content increased gradually with depth, especially in Pedon 3, where several strata exceeded the threshold for a gypsic horizon. This buildup reflects lowered slope and poor internal drainage, which concentrate sulfate and calcium that precipitate as gypsum crystals under high evaporation. This pattern results from active gypsification, one of the major processes shaping soils in the Lake Habbaniyah Basin.

Cation exchange capacity (CEC)

CEC increased progressively from Pedon 1 to Pedon 3, corresponding to the increase in clay content shown by the physical analyses. Clay minerals have greater surface area and exchange sites, so the finer texture of Pedon 3 also contributed to its higher CEC than the other pedons.

Soluble cations

Among soluble cations, calcium was most dominant, followed by magnesium, with sodium and potassium in the lowest concentrations. The high calcium content reflects the abundance of calcium carbonate and gypsum in the parent material, while the rising sodium concentration in Pedon 3 reflects salt accumulation from capillary rise of groundwater and evaporation. The predominance of calcium and magnesium indicates that the chemical regime remains governed by carbonate and gypsum minerals, limiting sodicity despite higher sodium in some strata.

Soluble anions

The results showed that the major anion was sulfate (SO_4^{2-}) followed by chloride and bicarbonate. The high sulfate content reflects the abundance of gypsum minerals in the parent material and subsurface horizons, while increasing chloride reflects evaporation and salt deposition at the low-lying sites. The decline in bicarbonate with depth reflects precipitation of calcium as calcium carbonate, lowering its concentration in the soil solution.

Sodium adsorption ratio (SAR) and exchangeable sodium percentage (ESP)

The SAR and ESP readings grew steadily with depth with the highest values in Pedon 3.

The rise in SAR and ESP with depth reflects greater salt accumulation at low-lying sites from poor drainage and rapid evaporation, though the dominance of calcium and magnesium limits sodicity in most horizons. These results suggest the soils are more salinized than sodic, a pattern common among desert soils in western Iraq. Comparison of the pedons shows a chemical gradient matching the topographic gradient: Pedon 1 had relatively low salinity, gypsum and calcium carbonate due to effective drainage and erosion; Pedon 2 was transitional with increasing accumulation; and Pedon 3 was highest in nearly all chemical indices, reflecting its low-lying position of sediment, water and salt accumulation. These results confirm that topography is the main factor controlling the chemical properties of soils in the basin, governing water movement, drainage efficiency and depositional sites, and thus the intensity of calcification, gypsification and salinization — directly reflected in diagnostic-horizon development and the differing classification of higher and lower sites, consistent with the study's aim.

3.5 Dominant Pedogenic Processes in the Soils of the Lake Habbaniyah Basin

The morphological, physical and chemical data show that soils in the basin were shaped by pedogenic processes whose intensity varied with topographic position. Differences in elevation, slope and drainage network restricted the circulation of water, dissolved substances and fine particles, producing different

degrees of profile development. The main processes were calcification, gypsification, salinization, addition and removal of material, erosion and deposition, and structural modification.

Calcification

Calcification was one of the most evident processes, shown by the steady increase in calcium carbonate with depth and field observations of calcareous filaments, nodules and concentrations in the Bk and Bky layers. It occurs as calcium carbonate dissolves under limited rainfall, moves short distances, and re-precipitates as evaporation increases and moisture declines, forming well-expressed calcic horizons. Calcification intensity was lowest in Pedon 1 due to elevation, increased in Pedon 2, and was greatest in Pedon 3 owing to lower slope and higher water retention favoring carbonate precipitation.

Gypsification

Gypsification increased markedly with depth, especially in Pedon 3, where gypsum crystals and concentrations in subsurface strata indicate active gypsification. This results from dissolution of gypsum minerals in the source material or via runoff, followed by re-precipitation as evaporation increases; the low-lying, poorly drained site concentrates sulfate and calcium, producing a well-developed gypsic horizon. This process is characteristic of dry-environment soils and is more intensive in the lower parts of the basin than in the higher areas.

Salinization

Electrical conductivity, soluble cations and anions, and high SAR and ESP values in Pedon 3 indicate active salinization, with salt concentrations increasing with depth and toward the lower sites. This results from deficient leaching, excessive evaporation and capillary rise of salt-bearing groundwater, followed by precipitation of salts as the water evaporates. Salinization was restricted in Pedon 1, moderate in Pedon 2, and well expressed in Pedon 3, with salt efflorescence and rising chloride and sulfate concentrations.

Additions and losses

Material addition and removal followed topographic position: elevated sites experienced continuous removal of fine particles by runoff and erosion, while lower sites received fine sediment and dissolved material transported from higher parts of the basin. The greater B-horizon thickness and higher clay and silt content of Pedon 3, relative to Pedon 1, confirm topography as the dominant factor controlling sediment distribution.

Erosion and deposition

Morphological and physical features clearly reflect erosion and deposition: Pedon 1's shallow profile and high sand content show the predominance of erosion and fine-particle removal.

Pedon 2 was a transitional zone with erosion and deposition roughly balanced, while Pedon 3's thicker horizons and greater clay and silt content reflect deposition of material from higher ground. These processes produced a marked differential in soil qualities across the basin, reflected in the degree of soil development.

Structural development and horizon differentiation

Structural development progressed from granular at the surface to subangular blocky, and in some deeper horizons to coarse blocky or prismatic structure, reflecting the ongoing accumulation of clay, carbonates and gypsum. Horizon differentiation also increased from Pedon 1 to Pedon 3: a calcic horizon occurred in all pedons, a gypsic horizon was well developed in Pedon 3, and pedogenic processes were most advanced in the lower sections.

Effect of topography on pedogenic processes

Topography is the most important factor in soil formation and development in the basin. At higher sites, steeper slopes increased runoff and erosion and shortened water residence time, limiting salt, carbonate and gypsum buildup and slowing horizon growth. At mid-slope sites, removal and addition of material were roughly balanced, allowing further profile development, while lower sites with less slope and poorer drainage favored deposition and higher moisture, supporting calcification, gypsification and salinization and forming more clearly defined diagnostic horizons.

3.6 Evaluation of the Degree of Pedogenic Development of the Pedons

Based on the morphological, physical and chemical properties, the pedons can be ranked by degree of pedogenic development as follows as shown in table 16:

Table 16. Degree of pedogenic development of the three pedons.

Pedon	Topographic position	Dominant pedogenic processes	Degree of development
P1	Upper	Erosion; incipient calcification	Weak to moderate
P2	Middle slope	Calcification; gypsification; deposition	Moderate
P3	Lower, near the lake	Calcification; gypsification; salinization; deposition	Moderate to advanced

These results show that topographic variation was the dominant factor controlling pedogenic processes and soil formation in the basin: differences in slope, elevation and drainage efficiency produced distinct erosion and deposition rates, reflected in fine-particle distribution, carbonate/gypsum/salt accumulation and horizon development. Pedon 1 had the lowest degree of development due to erosion dominance, Pedon 3 the highest due to deposition and accumulation, and Pedon 2 was transitional between the two.

3.7 Assessment of Soil Development in the Lake Habbaniyah Basin

Evaluating soil development is an important indicator of the strength of pedogenic processes and the influence of soil-forming variables on horizon formation and differentiation. The assessment used horizon differentiation, profile thickness, structural development, particle-size distribution, and calcium carbonate, gypsum and salt accumulation, together with parent material and topographic position. The results indicate that the degree of soil development in the basin is controlled by topographic position, since elevation, slope and drainage network govern erosion, deposition and water movement, producing clear variation in the intensity of pedogenic processes and horizon development.

Evaluation of Pedon 1 (P1)

Pedon 1, at the top of the basin, is dominated by erosion rather than deposition, shown by a relatively thin profile, poor horizon differentiation and a weakly formed calcic horizon.

It also had a comparatively coarse surface texture and low clay and organic-matter content, with relatively low EC and gypsum values indicating restricted salt and secondary-mineral deposition. These features indicate that pedogenic processes are still at an early stage here, with ongoing erosion limiting further horizon development; this pedon is therefore weakly to moderately developed.

Evaluation of Pedon 2 (P2)

Pedon 2, at the intermediate position, has erosion and deposition roughly balanced, giving a thicker profile and more distinct horizons than Pedon 1. Results showed distinct calcic-horizon formation, an emerging gypsic horizon, and increasing clay content, CEC, and calcium carbonate and gypsum accumulation. The shift in structure from granular to subangular blocky further indicates improved soil structure and sustained

pedogenic activity. These indicators place Pedon 2 at an intermediate stage of development, transitional between the less-developed upper soils and the more-developed lower soils.

Evaluation of Pedon 3 (P3)

Pedon 3, closest to Lake Habbaniyah, is the site most exposed to deposition and accumulation of fine particles and salts. It showed increased profile thickness, clearly expressed genetic horizons, higher clay and silt content, well-developed structure, and the highest values of calcium carbonate, gypsum, EC and CEC. A clearly differentiated calcic horizon and distinct gypsic horizon were observed, along with salinization patterns in some strata, indicating sustained pedogenic activity under restricted drainage and high evaporation. These indicators show that Pedon 3 has the highest degree of pedogenic development of the three, favored by conditions suited to secondary-material accumulation and diagnostic-horizon formation in table 17.

Table 17. Comparison of the principal indicators used in evaluating soil development.

Indicator	P1	P2	P3
Profile thickness	Moderate	Large	Very large
Horizon differentiation	Weak	Moderate	Clear
Structural development	Weak	Moderate	Good
Calcium carbonate accumulation	Moderate	High	Very high
Gypsum accumulation	Low	Moderate	High
Salinization	Weak	Moderate	High
Clay content	Low	Moderate	High
Intensity of pedogenic processes	Weak	Moderate	High
Degree of soil development	Weak-moderate	Moderate	Moderate-advanced

3.8 Role of Topography in Soil Development

Topography was the most important factor controlling soil development in the basin. At higher sites, steeper slopes increased runoff and removal of fine particles, restricting horizon growth; at mid-slope sites, removal and deposition were balanced, enhancing soil thickness and development; and at lower sites, gentler slope and poor drainage favored accumulation of fine sediments, calcium carbonate, gypsum and salts, promoting diagnostic-horizon formation and greater development. These results show that the basin's topographic gradient produced a corresponding gradient in soil development, greatest from the higher to the lower locations.

Based on the results of the study the degree of soil development in the Lake Habbaniyah Basin can be ranked as : Pedon 3 (P3) > Pedon 2 (P2) > Pedon 1 (P1)

This ranking reflects the direct effect of topography on pedogenic intensity: lower-area soils were more developed due to dominant deposition, calcification, gypsification and salinization, while soils at elevated sites were less developed due to dominant erosion, confirming topography as the governing factor in soil formation and development in the basin.

3.9 Classification of the Soils under the USDA Soil Taxonomy

The Keys to Soil Taxonomy [22] was used to classify the soils based on morphological description, physical and chemical analyses, diagnostic-horizon identification, and soil moisture and temperature regimes. All pedons occur in an arid to semi-arid environment dominated by calcification and gypsification, with no argillic horizons, indicating that soil development is mainly associated with carbonate and gypsum accumulation under limited leaching and high evaporation in table 18.

Table 18. Taxonomic classification of the studied pedons.

Pedon No.	Order	Suborder	Great group	Subgroup	Family
1	Aridisols	Calcids	Haplocalcids	Typic Haplocalcids	Fine-loamy, mixed, calcareous, hyperthermic Typic Haplocalcids
2	Aridisols	Gypsid	Haplogypsid	Typic Haplogypsid	Fine, mixed, gypsic, hyperthermic Typic Haplogypsid
3	Aridisols	Gypsid	Haplogypsid	Typic Haplogypsid	Fine, mixed, gypsic, hyperthermic Typic Haplogypsid

Pedon 1, on a relatively well-drained high spot, developed a well-expressed calcic horizon with high calcium carbonate content, but gypsum content did not meet the criterion for a gypsic horizon; with no argillic or natric horizons present, it is classed as Typic Haplocalcids.

In Pedon 2, gypsum accumulation is clearly higher in the Bky horizon, and although the calcic horizon is still present, the gypsic horizon is the more dominant diagnostic feature, placing the classification in the Gypsid suborder.

Pedon 3 is the most developed profile, with maximum gypsum and calcium carbonate content, a fully expressed gypsic horizon and high salinity, reflecting the prevalence of gypsification; it is classed as Typic Haplogypsid.

All soils of the study area are classified under Aridisols, consistent with the arid climate of the basin, where evaporation exceeds precipitation, limiting leaching and favoring carbonate and gypsum accumulation.

Taxonomic units differed clearly with topographic position: Pedon 1, limited to a calcic horizon, fell in the Calcids suborder, while Pedons 2 and 3, at the middle and lower sites, developed well-expressed gypsic horizons and fell in the Gypsid suborder.

These results confirm topography as a key factor in soil development in the basin, limiting the circulation of water, sediments and salts and controlling the diagnostic horizons on which USDA classification is based.

4 .Conclusions

1. The morphometric analysis showed clear variation in the basin's topographic characteristics (elevation, slope, drainage network), producing differing conditions for soil formation among the upper, middle and lower sites; this was confirmed by the morphological description, which showed corresponding variation in profile thickness, horizon differentiation, structural development, root distribution, and calcium carbonate/gypsum accumulation.
2. The physical and chemical properties both showed clear gradients toward the lower areas: sand decreased while silt and clay increased (improving water retention), and electrical conductivity, calcium carbonate, gypsum, SAR and ESP progressively increased, reflecting limited leaching and high evaporation, while all soils remained neutral to slightly alkaline.
3. Calcification was a principal pedogenic process in all pedons, producing well-expressed calcic horizons through the movement and re-precipitation of calcium carbonate, while gypsification dominated at the middle and lower positions, forming well-developed gypsic horizons from calcium sulphate accumulation, but remained limited at the elevated site.
4. Evaluation of soil development revealed a clear gradient — Pedon 1 least developed, Pedon 2 moderately developed, and Pedon 3 most developed due to carbonate, gypsum and salt accumulation —

consistent with the diagnostic horizons identified: an Ochric epipedon in all pedons, a Calcic horizon in all profiles, and a Gypsic horizon in Pedons 2 and 3.

5. Classification under the USDA Soil Taxonomy placed all soils in the order Aridisols, differing at the suborder level: Pedon 1 in the Calcids suborder, and Pedons 2 and 3 in the Gypsid suborder due to the dominance of gypsification.

6. The results confirm that topography is the most influential factor in soil formation and development within the Lake Habbaniyah Basin, controlling water, sediment and salt movement, the intensity of pedogenic processes, diagnostic-horizon formation, and consequently soil classification and degree of development.

References

- Abu Sufyah, A. A. K. (2007).** *Soil science: Principles and concepts* [In Arabic]. Dar Al-Masirah for Publishing and Distribution.
- Al-Bina, A. N., & Al-Hadithi, S. H. (2011).** *Fundamentals of soil science* [In Arabic]. University of Baghdad, College of Agriculture.
- Al-Hadithi, S. H., & Al-Bina, A. N. (2014).** *Land and soil classification* [In Arabic]. University of Baghdad, College of Agriculture.
- Al-Rawi, K. M., & Khalaf Allah, A. M. (2000).** *Design and analysis of agricultural experiments* [In Arabic]. Ministry of Higher Education and Scientific Research, University of Mosul.
- Al-Samarrai, A. S. A. (2010).** *Applied soil science* [In Arabic]. University of Baghdad, College of Agriculture.
- Al-Zubaidi, A. A. (2012).** *Geomorphology of arid lands* [In Arabic]. Dar Al-Kutub for Printing and Publishing, University of Mosul.
- Birkeland, P. W. (1999).** *Soils and geomorphology* (3rd ed.). Oxford University Press.
- Bockheim, J. G., Gennadiyev, A. N., Hartemink, A. E., & Brevik, E. C. (2014).** Soil-forming factors and Soil Taxonomy. *Geoderma*, 226–227, 231–237.
- Brady, N. C., & Weil, R. R. (2017).** *The nature and properties of soils* (15th ed.). Pearson.
- Buol, S. W., Southard, R. J., Graham, R. C., & McDaniel, P. A. (2011).** *Soil genesis and classification* (6th ed.). Wiley.
- Dent, D., & Young, A. (1981).** *Soil survey and land evaluation*. George Allen & Unwin.
- Food and Agriculture Organization of the United Nations. (2006).** *Guidelines for soil description* (4th ed.).
- General Directorate of Surveying. (n.d.).** *Topographic maps of Iraq, scales 1:100,000 and 1:250,000* [Maps in Arabic].
- Hillel, D. (2004).** *Introduction to environmental soil physics*. Elsevier.
- Iraqi Meteorological Organization and Seismology. (2024).** *Climatic data for Al-Anbar Governorate* [In Arabic].
- Iraqi Ministry of Water Resources. (n.d.).** *Studies on the Lake Habbaniyah Basin and water resources in Al-Anbar Governorate* [Reports in Arabic].
- IUSS Working Group WRB. (2022).** *World reference base for soil resources 2022* (4th ed.). International Union of Soil Sciences.
- Jenny, H. (1994).** *Factors of soil formation: A system of quantitative pedology*. Dover Publications. (Original work published 1941)
- McBratney, A. B., Minasny, B., & Stockmann, U. (2014).** Pedometrics for digital soil mapping. *Geoderma*, 214–215, 1–2.
- Schoeneberger, P. J., Wysocki, D. A., Benham, E. C., & Soil Survey Staff. (2012).** *Field book for describing and sampling soils* (Version 3.0). U.S. Department of Agriculture, Natural Resources Conservation Service.

- Soil Science Division Staff. (2017).** *Soil survey manual* (C. Ditzler, K. Scheffe, & H. C. Monger, Eds.; USDA Handbook No. 18). Government Printing Office.
- Soil Survey Staff. (1999).** *Soil taxonomy: A basic system of soil classification for making and interpreting soil surveys* (2nd ed., Agriculture Handbook No. 436). U.S. Department of Agriculture, Natural Resources Conservation Service.
- Soil Survey Staff. (2022).** *Keys to soil taxonomy* (13th ed.). U.S. Department of Agriculture, Natural Resources Conservation Service.
- Sparks, D. L. (Ed.). (1996).** *Methods of soil analysis: Part 3. Chemical methods*. Soil Science Society of America; American Society of Agronomy.
- Strahler, A. N. (1964).** Quantitative geomorphology of drainage basins and channel networks. In V. T. Chow (Ed.), *Handbook of applied hydrology* (pp. 4-39–4-76). McGraw-Hill.
- Zinck, J. A. (2012).** *Geomorphology and soils*. International Institute for Aerospace Survey and Earth Sciences.