



MASTERARBEIT | MASTER'S THESIS

Titel | Title

Soil hydraulic conductivity and soil properties in soda pans in
Seewinkel, Austria

verfasst von | submitted by

Maximilian Juhasz B.Sc. BEd

angestrebter akademischer Grad | in partial fulfilment of the requirements for the degree of
Master of Science (MSc)

Wien | Vienna, 2025

Studienkennzahl lt. Studienblatt | Degree
programme code as it appears on the
student record sheet:

UA 066 855

Studienrichtung lt. Studienblatt | Degree
programme as it appears on the student
record sheet:

Masterstudium Geography: Global Change and
Sustainability

Betreut von | Supervisor:

Univ.-Prof. Dipl.-Geogr. Dr. Stephan Glatzel

Acknowledgment

First of all, I would like to thank my supervisor Stephan Glatzel (University of Vienna, Department of Geography – Geoecology Working Group) for his prompt responses and review of this work. I am also grateful to Alfred-Paul Blaschke (TU Wien, Institute of Hydrology and Water Resource Management), who provided the idea for this study and supported the thesis by lending equipment and sharing his knowledge of the situation in Seewinkel.

Additional support at the University of Vienna came from Susanne Gier (Department of Geology), Franz Jirsa, and Andreas Gradwohl (both Department of Inorganic Chemistry). They offered unbureaucratic and timely assistance with crucial measurements conducted for this study namely, X-ray diffraction for soil mineralogy (Susanne Gier) and AES measurements for the quantification of soil cations (Franz Jirsa and Andreas Gradwohl). Without their help, this study would not have been possible. I would also like to thank Camila Aguetoni Cambui and Beatrix Bethke (both Department of Geography – Geoecology Working Group) for their support in the laboratory.

Outside the university, I would like to express my gratitude to two men "on the ground": Arno Cimadom (National Park Seewinkel) and Philipp Reiner (State of Burgenland), who assisted with organizing my fieldwork. I also thank Hans Unterfrauner (TB Unterfrauner) for his advice and for lending essential soil science equipment, as well as both of my employers at Ruralplan Ziviltechniker GmbH for their flexibility regarding working hours.

Lastly, I thank all others who supported me in small ways or simply with their attention during this thesis, especially my family, spouse, and friends.

Abstract (English)

This study measured k_f values and subsequent soil hydraulic conductivity (SHC), as well as topsoil (8 – 12 cm) and subsoil (40 – 50 cm) properties along transects consisting of five measurement points across the lakebeds of three Austrian soda pans: Martenhoflacke, Moschadolacke, and Illmitzer Zicksee. The aim of this study was the quantification of SHC within soda pans, as well as determining its connection with soil salinity and other relevant parameters.

Average SHC, obtained using a single-ring "Standrohr" infiltrometer, ranged from a mean of $k_f = 9.12 \times 10^{-9}$ m/s in Martenhoflacke to $k_f = 2.04 \times 10^{-8}$ m/s in Illmitzer Zicksee, and $k_f = 1.86 \times 10^{-7}$ m/s in Moschadolacke. The lowest SHC was recorded near the center of Martenhoflacke ($k_f = -7.76 \times 10^{-10}$ m/s), while two sites did not yield k_f values due to extremely low permeability. Furthermore, fully plant-covered sites across all soda pans exhibited significantly higher SHC values ($k_f = 2.75 \times 10^{-7}$ m/s) compared to sites without full plant cover ($k_f = 3.89 \times 10^{-9}$ m/s). All quantified soil properties (pH, electrical conductivity, soil texture, soil exchangeable and soluble Na^+ , K^+ , Mg^{2+} , and Ca^{2+} , organic and inorganic carbon, water content, bulk density, as well as derived values), along with principal component analysis (PCA) factors, were correlated with SHC. The strongest overall positive ordinary least squares (OLS) correlation between SHC and a single soil property was found for topsoil relative organic carbon content ($R^2 = 0.775$, $p < 0.05$), while topsoil pH showed the strongest negative OLS correlation with SHC ($R^2 = 0.551$, $p < 0.05$). In the subsoil, the strongest positive correlations were observed for fine silt content ($R^2 = 0.472$, $p < 0.05$) and exchangeable Mg^{2+} ($R^2 = 0.471$, $p < 0.05$).

PCA yielded four principal components (PC) for topsoil and three for subsoil properties respectively, together explaining more than 85% of the total variance. Topsoil PC1 ($\approx 44\%$ of variance), connected primarily with soil ion related properties, showed the strongest negative correlation with SHC ($R^2 = 0.61$, $p < 0.05$). In the subsoil, only PC2 ($\approx 21.8\%$ of variance) showed a significant positive correlation with SHC ($R^2 = 0.389$, $p < 0.05$). Lastly, clay mineral examinations in the lakebed center confirmed illite, chlorite and protodolomite across all soda pans and smectite only in Illmitzer Zicksee.

Based on the results, topsoil dispersivity was identified as a major driver of low SHC in soda pans. However, the precise role of organic carbon and plant cover, and their complex interplay with soil ion content, as well as the mechanisms behind saline soil formation and persistence, require further examination. Topsoil texture and subsoil properties, had a lesser impact on SHC measured within this study. Prolonged periods under water saturation were not directly linked to low SHC in saline soils, instead the shape of the lakebed was an explanation of differences in water saturation times. Furthermore, the distribution of low SHC areas along the elevation gradient varied between Martenhoflacke and Illmitzer Zicksee, whereby Martenhoflacke only showed low SHC in the central, low elevation areas and Illmitzer Zicksee exhibited low SHC along the whole elevation gradient. Moreover, clay mineralogical differences influence the formation of shrinkage cracks in saline soils and could have led to changes in saline soil SHC between Martenhoflacke and Illmitzer Zicksee.

Abstract (Deutsch)

In der folgenden Studie wurden k_f -Werte (auf 10°C korrigiert) und Bodenmerkmale im Oberboden (8–12 cm) und Unterboden (40–50 cm) entlang von Transekten mit jeweils fünf Messpunkten in den Böden dreier Salzlacken (Martenhoflacke, Moschadolacke und Illmitzer Zicksee) im österreichischen Seewinkel gemessen. Untersucht wurden zudem die Bodenparameter pH-Wert, elektrische Leitfähigkeit, Textur, Gehalte an löslichen und austauschbaren Kationen (Na^+ , K^+ , Mg^{2+} , Ca^{2+}), Kohlenstoffgehalte, Wassergehalt, Lagerungsdichte sowie abgeleitete Größen. Das Ziel der vorliegenden Studie war es die Wasserdurchlässigkeit in Salzlacken zu quantifizieren und Verbindungen mit relevanten Bodenparametern zu untersuchen.

Die durchschnittlichen k_f -Werte, gemessen mit einem Standrohrinfiltrometer, reichten von $k_f = 9,12 \times 10^{-9}$ m/s in der Martenhoflacke über $k_f = 2,04 \times 10^{-8}$ m/s im Illmitzer Zicksee bis $k_f = 1,86 \times 10^{-7}$ m/s in der Moschadolacke. Die niedrigsten k_f -Werte wurden im Zentrum der Martenhoflacke gemessen ($k_f = -7,76 \times 10^{-10}$ m/s). Flächen mit vollständiger Vegetationsbedeckung zeigten höhere k_f -Werte ($k_f = 2,75 \times 10^{-7}$ m/s) als solche ohne vollständige Bedeckung ($k_f = 3,89 \times 10^{-9}$ m/s). Die stärkste positive Korrelation zeigte sich zwischen k_f -Werten und dem Gehalt an organischem Kohlenstoff im Oberboden ($R^2 = 0,775$; $p < 0,05$), während der pH-Wert des Oberbodens die stärkste negative Korrelation aufwies ($R^2 = 0,551$, $p < 0,05$). Im Unterboden waren vor allem der Schluffgehalt ($R^2 = 0,472$, $p < 0,05$) und austauschbares Mg^{2+} ($R^2 = 0,471$; $p < 0,05$) positiv mit den k_f -Werten assoziiert. Mithilfe einer Principal Component Analysis wurden jeweils vier (Oberboden) und drei (Unterboden) Komponenten (PC) der Bodeneigenschaften identifiziert, welche über 85 % der Gesamtvarianz erklärten. Im Oberboden wies PC1 ($\approx 44\%$ der Varianz), welcher hauptsächlich mit den löslichen und austauschbaren Kationen in Zusammenhang stand, die deutlichste negative Korrelation mit den ermittelten k_f -Werten auf ($R^2 = 0,61$; $p < 0,05$). Im Unterboden zeigte nur PC2 ($\approx 21,8\%$ der Varianz) eine signifikante positive Korrelation mit der SHC ($R^2 = 0,389$; $p < 0,05$). Tonmineralanalysen im Zentrum der Salzlacken ergaben eine Dominanz von Illit und Chlorit, sowie Vorkommen von Protodolomit, während Smektit nur im Illmitzer Zicksee nachgewiesen werden konnte.

Die Ergebnisse deuten darauf hin, dass die Dispergierbarkeit des Oberbodens eine zentrale Rolle in der niedrigen Wasserleitfähigkeit der Salzlackenböden spielt. Die Rolle von organischem Kohlenstoff und Vegetation, sowie deren Wechselwirkungen mit dem Ionenhaushalt des Bodens und die Mechanismen der Salzbodenbildung bedürfen jedoch weiterer Untersuchungen. Im Vergleich dazu sind sowohl die Bodentextur im Oberboden als auch Eigenschaften des Unterbodens von geringerer Bedeutung für die ermittelten k_f -Werte. Die Studie konnte nicht bestätigen, dass niedrigere k_f -Werte direkt zu längeren Phasen der Wasserführung führen. Tonmineralogische Unterschiede könnten ebenfalls zu unterschiedlichen k_f -Werten in Martenhoflacke und Illmitzer Zicksee beigetragen haben, etwa durch Unterschiede in der Bildung von Schrumpfrissen. Zudem zeigte sich eine unterschiedliche räumliche Verteilung niedriger k_f -Werte entlang eines Höhengradienten: Während in der Martenhoflacke nur zentrale, tiefer gelegene Bereiche niedrige k_f -Werte aufwiesen, traten geringe k_f -Werte im Illmitzer Zicksee flächendeckend über den gesamten Höhengradienten hinweg auf.

Table of content

1. Introduction and background	10
1.1. Study area	10
1.1.1. Climate	11
1.1.2. Geology and groundwater	12
1.2. Water movement in soils	13
1.3. Saline soils and SHC	17
1.3.1. Soil structural stability and dispersibility	17
1.3.2. Influence of cations and related soil properties on SHC	18
1.3.3. Indices for soil structural stability and soil salinity	19
1.3.4. Experimental basis of SHC in saline soils	19
1.3.5. Saline soil types in Austria	20
1.3.6. Saline soil formation	21
1.4. Soda pans in Seewinkel	22
1.4.1. Geomorphological origin of soda pans	22
1.4.2. Geomorphological origin of a saline horizon	23
1.4.3. Concept of hydrological functionality	24
1.4.4. Sampled soda pans – description	25
1.5. Research objectives	27
2. Materials and methods	28
2.1. Study design, sampling and SHC measurements	28
2.2. Measurement of soil properties	30
2.2.1. General preparation	30
2.2.2. Soil pH (pH)	30
2.2.3. Soil electrical conductivity (EC)	30
2.2.4. Soil texture (clay%, silt%, sand%)	31
2.2.5. Soil exchangeable cations and effective Cation Exchange Capacity (CEC_{eff})	31
2.2.6. Soil soluble cations and soil soluble salt content (saltmin)	32
2.2.7. Organic (OC%), inorganic carbon (IC%) and Carbonate content (Carb%)	34
2.2.8. X-Ray diffraction	34
2.2.9. Soil water content (WC), bulk density (BD) and soil particles >2 mm (>2mm%)	35
2.3. Further environmental and calculated parameters	35
2.4. Data analysis and interpretation	36
2.4.1. Calculation of raw k_f -values	36
2.4.2. Correction of raw k_f -values	36
2.4.3. Statistics and transformations – k_f values and soil properties	38
2.5. Methodological constraints	39
2.5.1. SHC measurements	39
2.5.2. SHC correction	39
2.5.3. Correction of soil texture and salt content	40
3. Results	41
3.1. Measurement results and evaluation: SHC	41
3.2. Measurement results: Soil properties	44
3.2.1. pH and electrical conductivity (EC)	44

3.2.2. Soil cation content	45
3.2.3. Soil cation content – derived values	51
3.2.4. Soil carbon content.....	54
3.2.5. Topsoil bulk density and water content	56
3.2.6. Soil texture	57
3.2.7. Soil and clay mineralogy.....	60
3.2.8. Soil cracks	60
3.3. Measurement evaluation: Soil properties	62
3.3.1. Classification: Saline soils on measurement sites.....	62
3.3.2. PCA: Topsoil properties	64
3.3.3. PCA: Subsoil properties.....	67
3.3.4. Correlations: SHC and principal components	70
3.3.5. Correlations: SHC and topsoil properties.....	70
3.3.6. Correlations: SHC and subsoil properties	72
4. Discussion	73
4.1. SHC in examined soda pans.....	73
4.2. SHC and soil properties	74
4.2.1. Interpretation of PCA results	74
4.2.2. PCA results and SHC	74
4.2.3. Organic Carbon OC%.....	76
4.2.4. Soil ion content, pH and EC.....	77
4.2.5. Bulk density (BD) and soil gravel content (>2mm%)	79
4.2.6. Soil and clay mineralogy.....	81
4.2.7. Fine soil texture	82
4.3. SHC, water saturation and elevation	83
4.4. Further considerations	85
4.4.1. Authigenic mineral formation in soda pans	85
4.4.2. Groundwater levels and SHC	87
4.5. Conclusion	88
5. References	90
6. Appendix.....	98
6.1. Measurement sites – additional information	98
6.1.1. Geographical coordinates and heights.....	98
6.1.2. Pictures of selected measurement sites	99
6.2. Methods: Soil ion content – linear calibration slopes.....	104
6.3. Results: SHC measurements – raw data	106
6.4. Results: transformed soil properties	111
6.5. Results: PCA – Principal components.....	114
6.6. Results: PCA factor correlations.....	115
6.7. Results: soil mineralogy	117
6.7.1. Bulk soil mineralogy.....	117
6.7.2. Clay mineralogy	124

Figures

Figure 1: Examined soda pans and measurement sites	10
Figure 2: Climate diagram for Apetlon 1991 – 2020 (Geosphere Austria, 2020).	11
Figure 3 Dependence of volume flow on parameters.	13
Figure 4 Darcy's law.	13
Figure 5: Matrix potential and gravitational potential during equilibrium, infiltration and capillary rise (after Blume et al., 2010).	14
Figure 6: Distinguished zones during soil water infiltration (after Blume et al., 2010).	15
Figure 7: Hydraulic conductivity in different soils according to matrix potential (Figure adapted from Blume et al. 2010, p. 234).	16
Figure 8: Stern and diffuse layer at a surface charge density of σ and a Debye length of d (Figure from Hernandez, 2023 p. 6).	17
Figure 9: Formulas for the calculation of ESP, SAR and CROSS	19
Figure 10: Type 1 soda pans under high groundwater ("Hochwasser") and low groundwater ("Niederwasser") conditions according to Steiner, 2006 p. 64.	24
Figure 11: Type 2 and 3 soda pans under high groundwater ("Hochwasser") and low groundwater ("Niederwasser") conditions according to Steiner, 2006 p. 64.	24
Figure 12: Schematic representation of a "Standrohr" infiltrometer and relevant parameters.	29
Figure 13: Calculation of EC_e from $EC(2:3)$ values.	30
Figure 14: Calculation of clay mass from a 20 mL suspension aliquot.	31
Figure 15: Calculation of molar and mols of charge cation saturation for Na^+	32
Figure 16: Calculation of $salt_{min} \%$	33
Figure 17: Calculation of k_f and co-variables.	36
Figure 18: Approximation of water density of the liquid phase at 1000 hPa after Abascal and Vega, 2005.	36
Figure 19: Calculation of the viscosity correction factor for a given temperature after Österreichisches Normungsinstitut, 2002a.	37
Figure 20: SHC measurement results in each soda pans' measurement site (blue: Martenhoflacke, red: Moschadolacke, yellow: Illmitzer Zicksee).	42
Figure 21: Plant cover status and $k_{f, 10^\circ C, corr}$ results.	43
Figure 22: Results of relative topsoil and subsoil soluble cation content on each measurement site (yellow: $Na(H_2O\%)$, green: $K(H_2O\%)$, grey: $Mg(H_2O\%)$, orange: $Ca(H_2O\%)$; filled symbols: topsoil, empty symbols: subsoil).	47
Figure 23: Results of topsoil and subsoil relative exchangeable cation content in meq-% on each measurement site (yellow: $Na(meq\%)$, green: $K(meq\%)$, grey: $Mg(meq\%)$, orange: $Ca(meq\%)$; filled symbols: topsoil, empty symbols: subsoil).	50
Figure 24: Graphical representation of measured fine soil texture.	59
Figure 25: Soil cracks on measurement sites Ma2, Zi3 and Zi4 at WC of ≈ 18 wt.%.	61
Figure 26: Results of $PC1_{up}$ – $PC4_{up}$ (blue = Martenhoflacke, red = Moschadolacke, orange = Illmitzer Zicksee).	65
Figure 27: Biplot of $PC1_{up}$ and $PC2_{up}$	66
Figure 28: Results of $PC1_{low}$ – $PC3_{low}$ (blue = Martenhoflacke, red = Moschadolacke, orange = Illmitzer Zicksee).	68
Figure 29: Biplot of $PC1_{low}$ and $PC2_{low}$	69
Figure 30: Statistically significant correlations of $\ln(k_{f, 10^\circ C, corr})$ (SHC, x-axis) and principal components.	70
Figure 31: Strong OLS correlations of $\ln(k_{f, 10^\circ C, corr})$ (SHC, x-axis) and topsoil parameters.	71

Tables

Table 1: Permeability classification and common k_f values found in various substrates.....	13
Table 2: Soil textures and commonly found k_f values (Blume et al., 2010).....	16
Table 3: Parameters of examined soda pans Martenhoflacke, Moschadolacke and Illmitzer Zicksee.....	25
Table 4: Overview of exchangeable cation derived variables and abbreviations.....	32
Table 5: Overview of soil soluble cation derived variables and abbreviations.....	33
Table 6: Overview on correlation and significance levels used in this study.....	38
Table 7: Difference between calculated and measured densities of water at relevant measurement temperatures and 1000 hPa (National Institute of Standards and Technology, 2025).....	40
Table 8: Results of k_f 10°C, corr measurements (M1, M2, M3) and plant cover status on each measurement site.....	41
Table 9: Summary statistics results of k_f 10°C, corr in all examined soda pans.....	41
Table 10: Statistical results of comparing SHC in all soda pans.....	43
Table 11: Statistical results of pairwise comparison of SHC (Kruskal-Wallis test).....	43
Table 12: Statistical results of pairwise comparison of SHC (PERMANOVA, n = 10 000).....	43
Tables 13: Comparison of SHC for plant cover status, summary statistics and statistical test results and comparison of SHC.....	43
Table 14: Results of topsoil and subsoil pH on each measurement site.....	44
Table 15: Results of topsoil and subsoil EC (2:3) in $\mu\text{S}/\text{cm}$ on each measurement site.....	44
Table 16: Results of topsoil and subsoil absolute soluble cation content on each measurement site.....	46
Table 17: Results of topsoil and subsoil relative soluble cation content on each measurement site.....	46
Table 18: Results of topsoil and subsoil relative exchangeable cation content in mol-% on each measurement site (variables: Na(mol%), K(mol%), Mg(mol%), Ca(mol%)).	48
Table 19: Results of topsoil and subsoil relative exchangeable cation content in meq% on each measurement site.....	48
Table 20: Results of topsoil and subsoil relative exchangeable cation content in mmol and meq on each measurement site (variables: Na(molc), K(molc), Mg(molc), Ca(molc)).	49
Table 21: Results of topsoil and subsoil $\text{CEC}_{\text{eff, AT}}$ in mmol/kg fine soil on each measurement site.....	51
Table 22: Results of topsoil and subsoil $\text{CEC}_{\text{eff, INT}}$ in meq/kg fine soil on each measurement site.....	51
Table 23: Results of topsoil and subsoil SAR on each measurement site.....	52
Table 24: Results of topsoil and subsoil CROSS on each measurement site.....	52
Table 25: Results of topsoil and subsoil minimal salt content in wt.% on each measurement site.....	53
Table 26: Results of topsoil and subsoil organic carbon content in wt.% on each measurement site. P_{cov} sites are marked green.....	55
Table 27: Results of topsoil and subsoil inorganic carbon content in wt.% on each measurement site.....	55
Table 28: Results of IC% derived topsoil and subsoil carbonate content in wt.% on each measurement site.....	55
Table 29: Results of topsoil bulk density in g/cm^3 on each measurement site.....	56
Table 30: Results of topsoil water content in wt.% on each measurement site.....	56
Table 31: Soil texture classification of measurement sites for Austrian and International classifications.....	57
Table 32: Results of topsoil and subsoil soil texture on each measurement site.....	58
Table 33: Relevant soil properties and saline soil classification on each measurement site.....	63
Table 34: Principal components for topsoil properties (PC_{up}).....	64
Tables 35: OLS correlation strengths of relevant principal components (topsoil PCA) and topsoil properties.....	64
Tables 36: OLS correlation strengths of relevant principal components (subsoil PCA) and subsoil properties.....	67
Table 37: Principal Components for subsoil properties (PC_{low}).....	67
Table 38: Results of OLS-correlations for SHC and principal components ((**): $p < 0.05$).....	70
Table 39: OLS correlation results of SHC and PCA examined topsoil properties ((**): $p < 0.05$).....	71
Table 40: Relevant OLS correlation strengths and significance level of topsoil properties and SHC.....	71
Table 41: OLS correlation results of SHC and PCA examined subsoil properties ((**): $p < 0.05$; (*): $p < 0.1$).....	72
Table 42: Relevant OLS correlation strengths and significance level of subsoil properties and SHC.....	72

Appendix

Appendix 1: Martenhoflacke, Ma2 a P_{uncov} site	99
Appendix 2: Martenhoflacke, Ma3 a P_{uncov} site	99
Appendix 3: Martenhoflacke, Ma5 a P_{cov} site	100
Appendix 4: Illmitzer Zicksee, Zi3 (towards Zi1 and Zi2) a P_{uncov} , recently water-saturated, site	100
Appendix 5: Illmitzer Zicksee, Zi4 a P_{uncov} site	101
Appendix 6: Illmitzer Zicksee, Zi5 a P_{cov} site	101
Appendix 7: Moschadolacke, Mo1 a P_{uncov} site	102
Appendix 8: Moschadolacke, Mo2 a P_{cov} site, fully covered with common reed	102
Appendix 9: Moschadolacke, Mo3 a P_{cov} site	103
Appendix 10: Moschadolacke, Mo5 a P_{cov} site	103
Appendix 11: linear calibration - Na^+	104
Appendix 12: linear calibration - K^+	104
Appendix 13: linear calibration - Mg^{2+}	105
Appendix 14: linear calibration- Ca^{2+}	105
Appendix 15: formula for logit transformation of variable p (%)	111
Appendix 16: Bulk soil mineralogy - topsoil Martenhoflacke	118
Appendix 17: Bulk soil mineralogy - subsoil Martenhoflacke	119
Appendix 18: Bulk soil mineralogy - topsoil Moschadolacke	120
Appendix 19: Bulk soil mineralogy - subsoil Moschadolacke	121
Appendix 20: Bulk soil mineralogy - topsoil Illmitzer Zicksee	122
Appendix 21 Bulk soil mineralogy - subsoil Illmitzer Zicksee	123
Appendix 22 Clay mineralogy - site Ma1, topsoil. X-ray diffraction patterns of the clay fraction, saturated with Mg, K, Mg and glycerol, K and ethylene glycol, and heated to 550 °C; d-values in Å	125
Appendix 23 Clay mineralogy - site Ma1, subsoil. X-ray diffraction patterns of the clay fraction, saturated with Mg, K, Mg and glycerol, K and ethylene glycol, and heated to 550 °C; d-values in Å	126
Appendix 24 Clay mineralogy - site Mo1, topsoil. X-ray diffraction patterns of the clay fraction, saturated with Mg, K, Mg and glycerol, K and ethylene glycol, and heated to 550 °C; d-values in Å	127
Appendix 25 Clay mineralogy - site Mo1, subsoil. X-ray diffraction patterns of the clay fraction, saturated with Mg, K, Mg and glycerol, K and ethylene glycol, and heated to 550 °C; d-values in Å	128
Appendix 26 Clay mineralogy - site Zi1, topsoil. X-ray diffraction patterns of the clay fraction, saturated with Mg, K, Mg and glycerol, K and ethylene glycol, and heated to 550 °C; d-values in Å	129
Appendix 27 Clay mineralogy - site Zi1, subsoil. X-ray diffraction patterns of the clay fraction, saturated with Mg, K, Mg and glycerol, K and ethylene glycol, and heated to 550 °C; d-values in Å	130

Appendix Tables

Appendix Table 1: MGI Austria GK East coordinates and height above adriatic sea of all measurement sites.	98
Appendix Table 2: Variable numbers, names and description for k_f measurement results table Appendix Table 3	106
Appendix Table 3: Variables – k_f measurements.	110
Appendix Table 4: Variable numbers, variable names and applied transformations.	111
Appendix Table 5: Variable numbers 1 – 14 transformed values on each site.	112
Appendix Table 6: Variable numbers 15 – 29 transformed values on each site.	113
Appendix Table 7: Numerical results of relevant PC for topsoil properties.	114
Appendix Table 8: Numerical results of relevant PC for subsoil properties.	114
Appendix Table 9: Topsoil properties PCA - correlations with Principal Components ($p < 0.05^{***}$, $p < 0.1^{**}$).	115
Appendix Table 10: Subsoil properties PCA - correlations with Principal Components ($p < 0.05^{***}$, $p < 0.1^{**}$).	116
Appendix Table 11: Abbreviations and mineral names – total bulk soil mineralogy	117
Appendix Table 12: Signals (2Theta) and corresponding minerals	124

1. Introduction and background

1.1. Study area

The study area, commonly known as Seewinkel, is located east of Austria's largest lake "Lake Neusiedl", usually confined by the Parndorf plateau to the North, the Austrian border to the East and by the Waasen/Hanság area to the south. The area extends approximately 300 km² while relief variations are not higher than 17 m (Draganits et al., 2022). From a soil science perspective, however, it has been argued that only the area directly Southeast (Nestroy and Kuttner, 2022) of Lake Neusiedl called "Lackenzone" can be defined as "Seewinkel". All in-field data collection took place in this area, namely east of Apetlon in soda pans "Martenhoflacke" and "Moschadolacke" as well as "Illmitzer Zicksee" Northwest of Illmitz (see Figure 1).



Figure 1: Examined soda pans and measurement sites
(bottom description: left = Martenhoflacke, center = Moschadolacke, right = Illmitzer Zicksee).

1.1.1. Climate

To describe the 1991 – 2020 climate period, SPARTACUS spatial monthly climate data analysis for Apetlon (lat 47.747757, lon 16.84958, ETRS89) was used (Geosphere Austria, 2020). Data shows a typically Pannonian climate with moderately cold winters and hot summers, as well as moderate levels of precipitation with a maximum in the summer months (Figure 2). The average temperature for the period 1961 – 1990 was 10.4°C, while the 1991 – 2020 temperature was 11.7°C, showing a warming of >1°C in the last decades. Yearly precipitation averaged 597 mm and 619 mm, respectively. Although precipitation is relatively high, several authors report semi-arid conditions largely caused by high evaporation during summer months (e.g. Eitzinger et al., 2009; GRUPPE WASSER, 2021; Häusler, 2023). However the classification as (semi-)arid is not shared amongst all authors (Draganits et al., 2022).

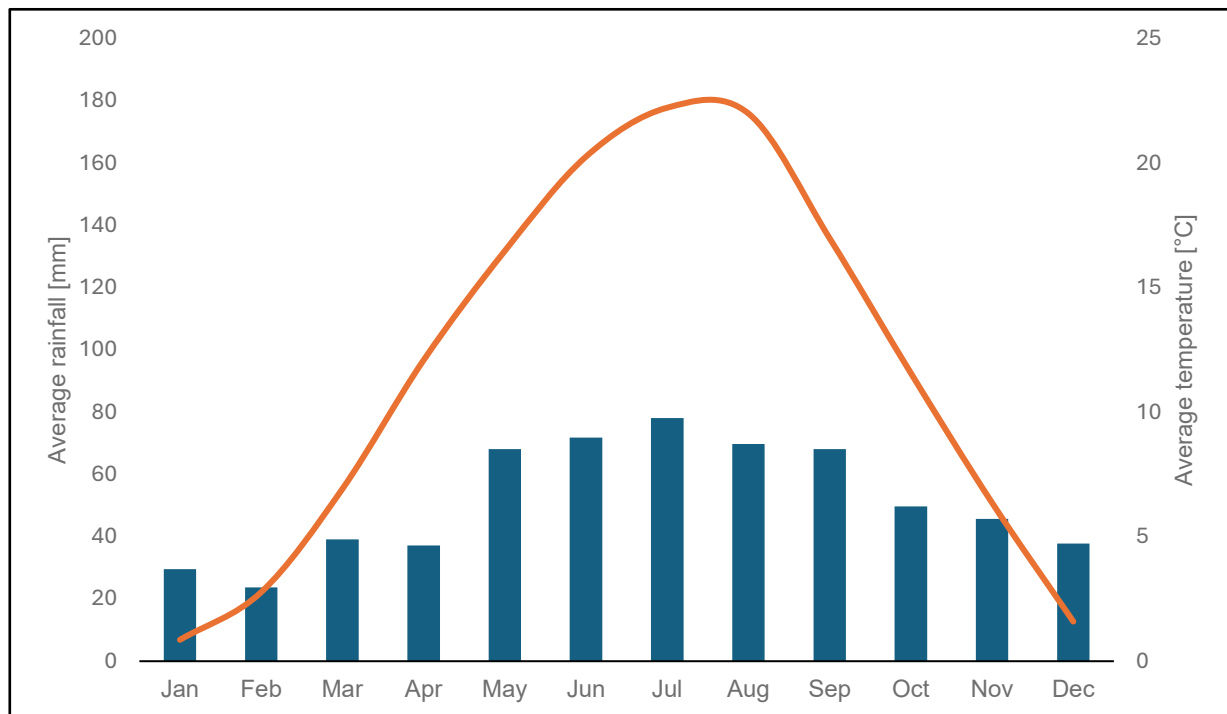


Figure 2: Climate diagram for Apetlon 1991 – 2020 (Geosphere Austria, 2020).

1.1.2. Geology and groundwater

The area of Lake Neusiedl and Seewinkel is located on Paleozoic and Mesozoic basal strata named “Kristallin”, which comprises metamorphic rocks at a depth of 1000 to 2500 m (Häusler, 2007). Furthermore, since the study area is located on the Western edge of the Pannonian basin, the whole area is subject to ongoing geological subsidence from West to East (Fuchs and Schreiber 1985 in Draganits et al., 2022). On top of this foundation layer, upper Miocene sediments are found. Finally, the near-surface geological consists of rubbly sediments “Seewinkelschotter” or “Illmitz-Formation” of Quaternary fluvial origin. It remains debated which fluvial system (namely the Danube or the Rába/Répcse system) is responsible for the deposition of these sediments. In any case, the gravel deposits are situated in the Riss glaciation (Häusler, 2023), while fine-grained saline deposits (“saline horizon”) also found in the area are likely to be temporally located in the Mindel/Riss interglacial. Both sediments are the basis for soil formation in the region (Nestroy and Kuttner, 2022).

Groundwater in Seewinkel consists of two main layers that are of high heterogeneity in terms of their depth, isotope content and horizontal as well as vertical permeabilities. According to isotope measurements, groundwater in the upper layer resides for years to decades and is linked to meteorology. Nevertheless, the upper groundwater layer comprises areas which do not show H^3 isotopes, therefore no groundwater formation from precipitation occurs in parts of Seewinkel. The lower groundwater level exhibits residence times of 100s to several 10.000 years (Baranyi et al., 1986; Dreher et al., 1986; Rank, 1986). The most recent study by Häusler, 2023 about the groundwater in Seewinkel and particularly around soda pans lists three distinct groundwater levels. The “second groundwater layer” is subdivided into an upper layer of Miocene origin and thermal groundwater in a third layer originating in the Neogene. However, more importantly the idea first proposed in the work of Gritzmam and Dober, 2014 (supervised by H. Häusler) of isolated groundwater bodies (IGB) in the upper groundwater layer was examined in detail. In this work, it was postulated that local groundwater bodies are IGBs and show increased salt contents due to evaporation processes (Gritzmam and Dober, 2014).

1.2. Water movement in soils

Soil hydraulic conductivity (SHC) is an important aspect of hydrological modelling, which is hard to represent due to its complexity and heterogeneity on a spatial scale. SHC is dependent on flow through highly tortuous soil pores (“matrix flow”) and/or relatively less tortuous cracks or biological “tunnels” created by biological or physical processes (“preferential flow”) (Vereecken et al., 2022).

To describe the hydraulic conductivity through pores, Henry Darcy in 1856 found that volume flow ($\dot{V}$) through sand is proportional to area (A), flow length (l), and difference of pressure height (h) (Figure 3). The hydraulic conductivity of a substrate can then be described by using the permeability coefficient k_f , which is defined by Darcy’s law as a substrate-specific proportional constant (Figure 4).

$$\dot{V} \sim A * \frac{h}{l}$$

Figure 3 Dependence of volume flow on parameters.

$$\dot{V} = k_f * A * \frac{h}{l}$$

Figure 4 Darcy’s law.

Due to its calculation, the SI unit of k_f is m/s, even though it does not describe a velocity. Furthermore, the k_f value is dependent on the viscosity of the substance, therefore temperature as a controlling factor of viscosity is important while measuring. Commonly, k_f values are strongly linked to substrate texture (Hölting and Coldewey, 2019). Table 1 shows a classification of permeability and an overview of common k_f values for different textures.

Table 1: Permeability classification and common k_f values found in various substrates.

Permeability	k_f [m/s]	Substrate texture	k_f [m/s]
Very high permeability	$> 10^{-2}$	Coarse sand	$\sim 10^{-3}$
High permeability	10^{-2} to 10^{-4}	Fine sand	10^{-4} to 10^{-5}
Normal permeability	10^{-4} to 10^{-6}	Silty sand	10^{-5} to 10^{-6}
Low permeability	10^{-6} to 10^{-8}	Clayey silt	10^{-6} to 10^{-9}
Very low permeability	$< 10^{-8}$	Clay	$< 10^{-9}$

Soils are more complicated than their initial substrates because they are not a homogenous substrate but a product of biological and geological processes. The “irregularities” due to soil aggregates or biopores can lead to anisotropic flow processes which are not only vertical but also horizontal. It is, however, assumed that Darcy’s law can also be attributed to soil because laminar flow conditions are generally valid in usual soil textures (sand, silt, clay). This holds both true for SHC under saturated conditions as well as water movement under unsaturated soil conditions. A major assumption in applying Darcy’s law is the stability of soil pores under saturated conditions (Blume et al., 2010). This assumption, however, is not generally met within soil, particularly not in saline soil (refer to chapter 1.3). In this work, whenever SHC is mentioned, saturated conditions are assumed, if not stated otherwise.

Three types of water movement through soil can be distinguished: 1) infiltration, 2) capillary rise, and 3) drainage. To understand these processes, one must understand the hydraulic potential (Ψ_H) and its main components: the matrix (Ψ_M) and gravitational (Ψ_z) potential ($\Psi_H = \Psi_M + \Psi_z$). The gravitational potential explains the vertical water movement driven by gravity and shows positive values above the groundwater level. The matrix potential describes all influences of the soil matrix on soil water and can be interpreted as a measure of how strong water is bound to the soil. Since Ψ_M is opposed to Ψ_z it is of negative value which decreases with decreasing water content. If no water movement occurs in soils the hydraulic potential is defined as $\Psi_H = 0$ and therefore soil water is in an equilibrium where $|\Psi_M| = |\Psi_z|$ (see Figure 5) (Blume et al., 2010).

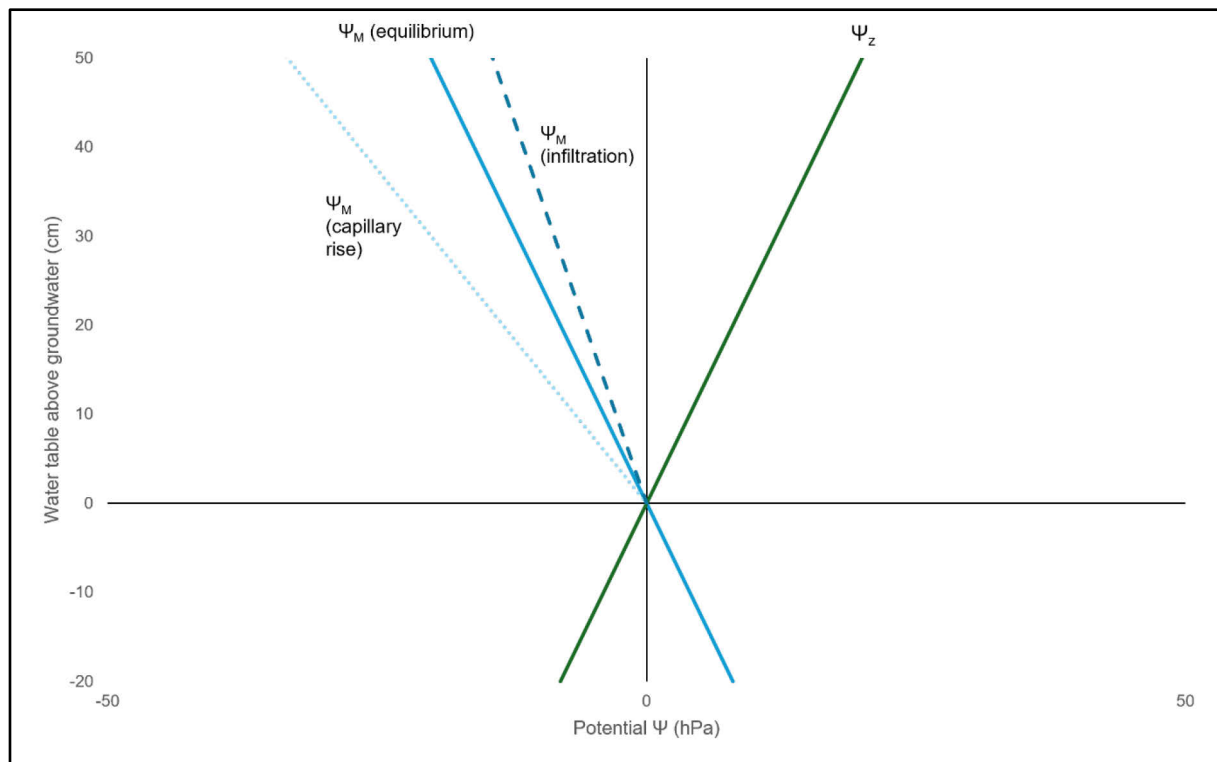


Figure 5: Matrix potential and gravitational potential during equilibrium, infiltration and capillary rise (after Blume et al., 2010).

Infiltration (1) is a movement of water from the soil surface to subsoil areas driven by a positive hydraulic potential (Ψ_H) resulting from a less negative Ψ_M through wetting and a constant gravitational force described by Ψ_z (see Figure 5). During the infiltration process, four zones are distinguished according to water content and movement which are depicted in Figure 6. In the beginning, saturated and transitioning zones are forming slowly, and the influence of unsaturated conditions described by Ψ_M is high, while transportation and wetting zones are increasing relatively fast along a hydraulic gradient. The further the transportation zone extends over time, the lower the influence of Ψ_M becomes, and the hydraulic potential is described by its gravitational component ($\Psi_H \approx \Psi_z$). Under field conditions, the velocity of water infiltration is dependent on the velocity of water movement in the transportation zone which usually reaches 70 – 80% of maximum soil saturation (Blume et al., 2010).

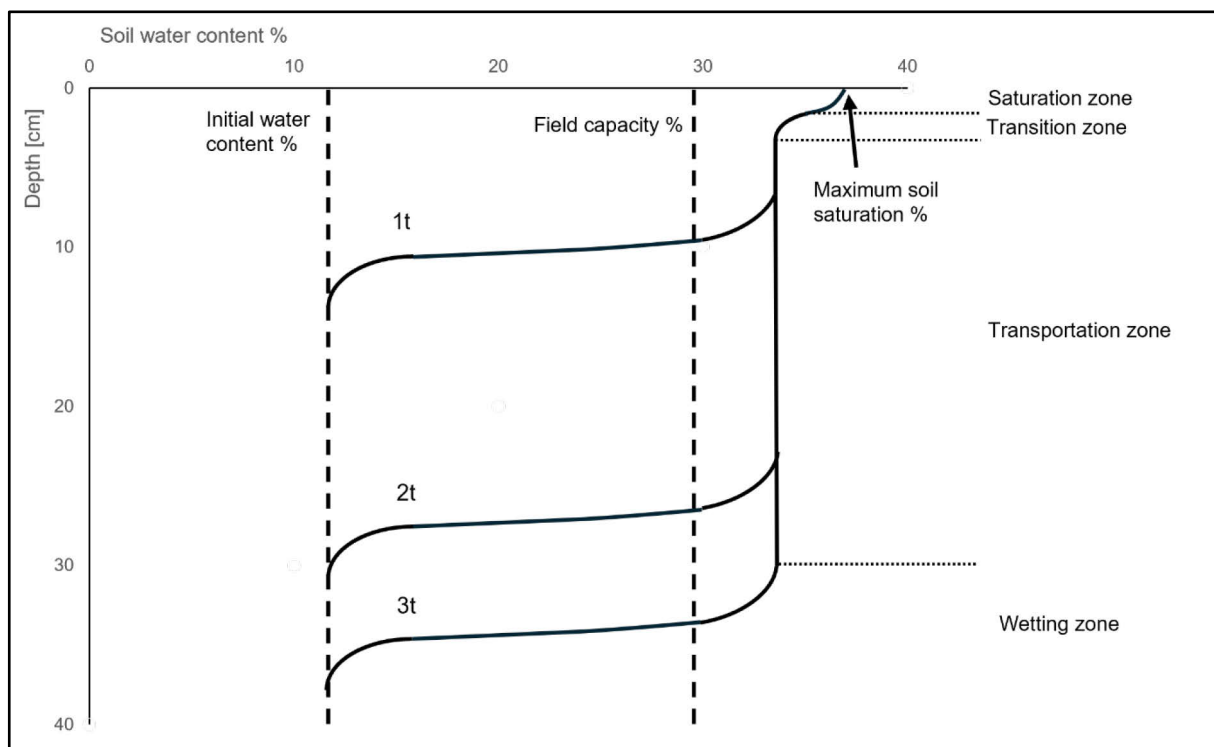


Figure 6: Distinguished zones during soil water infiltration (after Blume et al., 2010).

Under unsaturated conditions, hydraulic conductivity is smaller because of lower matrix potential (Ψ_M): While saturated conditions show a matrix potential $\Psi_M \approx 0$ hPa, the potential can decrease to $< -10^4$ hPa in unsaturated environments. With decreasing matrix potential and consequently less water saturation, particularly within larger pores, k_f values change from saturated sandy soil > silty soil > clayey soil to unsaturated clayey soil > silty soil > sandy soil (see Figure 7) (Blume et al., 2010).

Capillary rise (2) is a counter-directional bottom-up movement through capillary water movement in soil micropores. Since the height of capillary rise is indirectly dependent on pore radius and temperature, its effect is highly dependent on soil conditions. The movement generally occurs if Ψ_M on the surface decreases through water loss above the groundwater layer, for example, through evaporation. Consequently, the hydraulic potential becomes negative ($\Psi_H = \Psi_z + \Psi_M < 0$) (Figure 5). This process can lead to

deposition of substances dissolved in water transported upward, such as soluble salts. Lastly, drainage (3) is a process of decreasing groundwater levels and therefore increasing Ψ_z which consequently leads to lower Ψ_M in equilibrium. Therefore, particularly the topsoil loses humidity because of improved infiltration and less capillary rise close to the surface. This also implies that salts are drained from the topsoil through up-down infiltration (Blume et al., 2010).

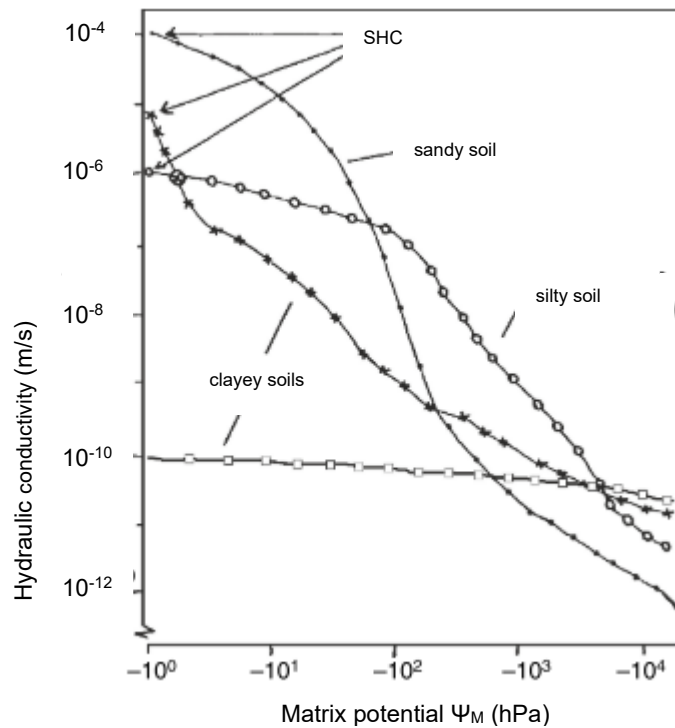


Figure 7: Hydraulic conductivity in different soils according to matrix potential (Figure adapted from Blume et al. 2010, p. 234).

Usually, the soil and substrate specific k_f values are utilized for measuring SHC. However several assumptions must be made: 1) the soil is homogenous, and no anisotropic flow occurs, 2) pores do not change through water infiltration and 3) the flow occurs under quasi-saturated conditions in a steady state. Furthermore, in-field measurements need to control as many variables as possible such as area and time of infiltration as well as infiltrated water volume, hydraulic potential and temperature of infiltrating liquid. Due to difficulties in controlling these factors and limited applicability of assumptions, as well as heterogeneity of soils on a spatial scale (measured), SHC is a soil parameter of high variability (Blume et al., 2010). Commonly measured k_f values in soils of varying textures are depicted in Table 2.

Table 2: Soil textures and commonly found k_f values (Blume et al., 2010).

Soil texture	k_f values [m/s]
Sand dominated	3.9×10^{-3} to 4.0×10^{-5}
Silt dominated	3.9×10^{-3} to 5.0×10^{-7}
Loam dominated	3.9×10^{-3} to 10^{-7}
Clay dominated	3.9×10^{-3} to 10^{-9}

1.3. Saline soils and SHC

1.3.1. Soil structural stability and dispersibility

Structural stability of dry (saline) soil on an atomic level is assumed to be dependent on ionic and covalent portions of bonds between negatively charged clay particles and positively charged cations (Marchuk, 2013). In reality, most bonds are neither covalent nor ionic, because in ionic bonds, electrons of the anion are attracted by the positive charge of the cation, and therefore, outer atomic orbitals are deformed towards each other (Mortimer and Müller, 2020).

In water, on the other hand, diffuse double layer forces are causing dispersion of particles (Quirk and Schofield, 1955): In suspension, the repulsive forces between suspended colloidal particles are named “double layer forces”. A surface within water acquires charges, for instance, by dissociation of acidic or basic groups or by binding ions from the solution. On a negatively charged surface, hydrated cations form a compact layer (“stern layer”) close to the surface and a diffuse layer defined by higher concentrations of hydrated cations above the stern layer (Figure 8). The thickness of this double layer, the Debye length, depends on temperature and electrolyte concentration. With increasing electrolyte concentration, the Debye length decreases because the stern layer on the particle surface is more pronounced, and it screens the charge of the surface, which attracts the second diffuse layer. Temperature is a controlling factor because, surprisingly, it is not the electrostatic charge but instead the entropic “mixing” force of ions in solution striving for a homogenous distribution, which is responsible for particle repulsion. This mixing force increases as the temperature rises (Hernández, 2023).

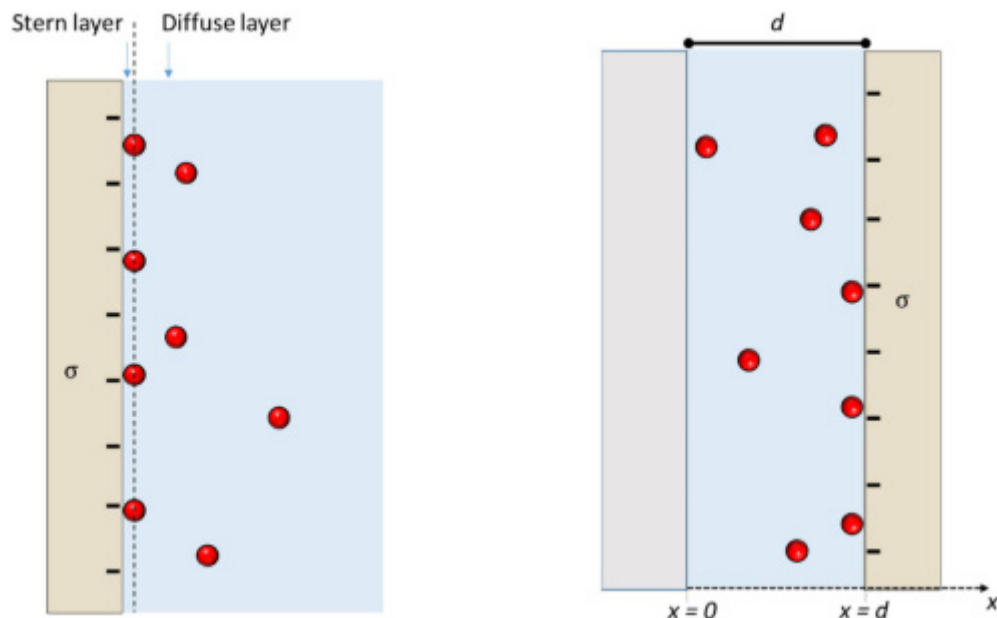


Figure 8: Stern and diffuse layer at a surface charge density of σ and a Debye length of d (Figure from Hernández, 2023 p. 6).

Other intermolecular forces, “Van-der-Waals” forces, which are close-range attracting forces caused by charge differences in atomic orbitals, are essential in understanding the circumstances under which coagulation occurs or how colloidal stability is

maintained. In case of dispersed particles, coagulation can only occur if the energy barrier posed by double layer forces can be overcome by short-range “Van-der-Waals” forces. This is the case if surface charge density or the size of particles is decreased, or else the ionic strength of the solution is increased. To measure surface charge density, for example, in clays, the zeta (ζ)-potential is used, whereby a high absolute ζ -potential signals a high colloidal stability or low tendency to coagulate (Hernández, 2023).

1.3.2. Influence of cations and related soil properties on SHC

Marchuk and Rengasamy, 2011 calculated the ionicity index (a measure for the degree of ionic bonds) of various cations from their radius, charge, and ionization potential, and compared the ionicity index to ζ -potentials of homoionic clay minerals. They found that, with decreasing ionicity indices in the order $\text{Na}^+ > \text{K}^+ > \text{Mg}^{2+} > \text{Ca}^{2+}$, the dispersive potential of clay minerals saturated with these cations also decreased. The dispersive potential was measured by solution turbidity, which followed exactly the order of decreasing ionicity indices, and by ζ -potential, which also followed the decreasing ionicity order. The linear relationship of turbidity relative to ionicity was positive and very pronounced ($R^2 = 0.93$) (Marchuk and Rengasamy, 2011). Since the ionicity index is essentially calculated from ion radius and charge, it also gives an approximation of hydration because hydration, or the tendency of water molecules to interact with ions, decreases with increasing radius and decreasing charge density (Mortimer and Müller, 2020). This uptake of water through hydration of ions in particles is then responsible for clay expansion or shrinking, which in turn decreases or increases pore volume (Blume et al., 2010).

Soil texture, as a measure of particle size, is relevant because with increasing particle size, the energy barrier for Van-der-Waals forces is decreased and therefore coagulation is facilitated. Furthermore, both cation exchange capacity and shrinking/expansive behavior of soils are highly dependent both on clay content and mineralogy influencing ζ -potentials (Blume et al., 2010). High soil pH also leads to higher surface charge density in negatively charged particles such as clay (measured by higher absolute ζ -potential) and therefore increases dispersivity of soils. Soil soluble salts and consequently EC can increase the ionic strength of the soil solution and therefore decrease the energy barrier for Van-der-Waals forces or coagulation. On the other hand, salts such as NaHCO_3 can increase soil pH and therefore increase dispersivity. Soil organic carbon plays an important part in cation exchange capacity (Blume et al., 2010) because it forms mostly covalent bonds with clay surfaces which decreases the ζ -potential (Marchuk, 2013). Inorganic carbon in carbonate can increase infiltrating water EC through dissolution, particularly through Ca^{2+} an important ion for structural stability (Shainberg and Letey, 1984; Shainberg and Oster, 1978). In natural saline soils, the effects of these soil properties are intertwined and complex (Marchuk, 2013).

1.3.3. Indices for soil structural stability and soil salinity

Indices for soil structural stability in salt affected soils are traditionally focused on exchangeable Na^+ . The amount of Na^+ can be measured as ESP (Exchangeable Sodium Percentage) or “sodium saturation” and by SAR (“Sodium Absorption Ratio”) (Figure 8). Since SAR does not distinguish between divalent cations Ca^{2+} and Mg^{2+} into account and does not include K^+ , Marchuk, 2013 proposed a new index, CROSS (Cation Ratio of Soil Structural Stability), which gives a more complete picture of soil structural stability in relation to exchangeable cations. Soluble salts are usually measured by EC or as total mass of soluble salts within soils (Blume et al., 2010). An important unit for quantifying cations on the exchanger surface in the international classification is meq or meq. (IUSS Working Group WRB, 2022). The ESP, SAR and CROSS are all calculated utilizing these units (Marchuk, 2013).

$$ESP = \frac{Na}{CEC} * 100$$
$$SAR = \frac{Na}{\sqrt{(Ca + Mg) * 0.5}}$$
$$CROSS = \frac{Na + 0.56K}{\sqrt{(Ca + 0.6Mg) * 0.5}}$$

Figure 9: Formulas for the calculation of ESP, SAR and CROSS

1.3.4. Experimental basis of SHC in saline soils

SHC studies in saline soils have a long scientific history because of their importance for irrigation in arid regions (Quirk and Schofield, 1955). The above-described tendency of water with higher EC values to infiltrate better into saline soils as well as the deleterious effects of cations on SHC has been quantified in several studies such as:

Quirk and Schofield, 1955 developed a threshold concentration of salts in infiltrating water to avoid a decrease in SHC of 10 – 15 % through particle dispersion. They found that in non-calcareous silty loams, threshold electrolyte concentrations were more than 10 times higher with an ESP of 21% as opposed to full Ca^{2+} saturation.

In their literature review, Shainberg and Letey, 1984 summarized the work of several previous authors¹ as follows: At lower ESP values (<15) soil dispersion usually is the driving factor for SHC reductions both in swelling and non-swelling soils. At ESP >15 in soils containing significant amounts of smectite-type clays, swelling induced by exchangeable Na^+ becomes the driving factor for SHC reductions. In general, SHC can be maintained if infiltrating solutions reach salt concentrations above the critical threshold concentration (CTC) which is soil specific and influenced by several factors such as soil clay content, bulk density, organic matter content, clay mineralogy and iron/aluminum oxide content. If soils were infiltrated with rainwater or distilled water,

¹ Refer to Shainberg and Letey (1984) for a full list of authors.

soluble minerals such as CaCO_3 or other salts are main factors in maintaining SHC of the soil.

Levy et al., 2005 found that slow and fast wetting of Na^+ affected packed substrates influenced the effect of ESP on SHC reduction. If soils were wetted slowly, significant reductions of SHC could only be observed at ESP = 20%, while in fast wetting scenarios, similar reductions were already observed at ESP 5 – 10%. The authors concluded that slow wetting minimized the destabilization of clay particles and therefore clay swelling was the main mechanism to reduce SHC.

Marchuk et al., 2012 in a non-destructive X-ray study on a Red Chromosol (Australian soil classification) dominated by illite and kaolinite showed that active porosity and pore connectivity of soils dominated by one cation were linearly correlated with SHC ($R^2 = 0.76$ and $R^2 = 0.97$). Consequently, SHC measured with deionized water decreased in the order of $\text{Ca}^{2+} > \text{Mg}^{2+} > \text{K}^+ > \text{Na}^+$ dominated soils, as predicted by ionicity. In the study, porosity measured by X-ray scanning was found to decrease in the same order as well. Consequently, not only Na^+ but also Mg^{2+} and particularly K^+ need to be considered for SHC reductions when present in high quantities.

1.3.5. Saline soil types in Austria

In Austria, saline or sodic soils occur mainly in the study area (Wolfram et al., 2006). The Austrian soil classification lists three types of saline soils: Solontschak, Solonetz and Solontschak-Solonetz, a mixed type. Furthermore, hydromorphic soils such as “Feuchtschwarzerde” or peat soils might be influenced by salt as well (Nestroy et al., 2011).

Solontschak soils are defined by high soluble salt content (0.3 wt.%) and electrical conductivity values (EC) of >4 mS/cm in the saturation extract. Na^+ and Mg^{2+} saturation of cation exchange capacity (CEC) is below 15% and 30% respectively. The pH values are between 8 and 9. Solonetz soils in Austria develop through superposition of Solontschaks with material of low salt content. They exhibit high Na^+ and/or Mg^{2+} saturation (>15 mol-% and >30 mol-% respectively) but salt contents below 0.3 wt.% and EC of <4 mS/cm in the saturation extract. The pH values are higher than 8.5, often higher than 9.5. Consequently, Solontschak-Solonetz soils are of a mixed type which show both high salt contents (>0.3 wt.%; $\text{EC} > 4$ mS/cm) and high Na^+ and/or Mg^{2+} saturation, pH values of these soils are similar to Solonetz. Both Solontschak and Solonetz soils exhibit poor soil structure, however the soils influenced by higher Na^+ and Mg^{2+} contents usually have a higher tendency to form deep cracks and show concrete-like hardness during dry periods (Nestroy et al., 2011). It is likely that most saline-sodic soils in soda pans are of a chemically mixed type Solontschak-Solonetz which exhibits both high soluble salt content and high Na^+ or Mg^{2+} saturation (Nelhiebel, 2001; Nestroy and Kuttner, 2022).

1.3.6. Saline soil formation

The formation of saline soils in Seewinkel is seen in relation to a saline deposition (“saline horizon”) and follows two different theories: According to Scherf, 1935 (in Häusler, 2023) saline soils developed on a saline horizon wherever the overlying layer of loamy Loess was close enough to accumulate salts due to groundwater salinization. In their influential work on Austrian saline soils Franz and Husz, 1961. However, theorized that Austrian Solontschaks were formed wherever the primary “saline horizon” was not overlain by other substrates. They note that Solonetz in Austria were not formed by falling groundwater levels on former Solonchak soils, but instead by superposition of Solonchak soils (geologically equal to the “saline horizon”) with non-saline sediments. Wherever the saline horizon was eroded away, saline soils are missing. The authors explicitly locate most of the saline soils in Western Seewinkel. The view of a direct development from a saline-horizon is shared by most influential authors (Krachler et al., 2012; Nelhiebel, 1977; Nestroy and Kuttner, 2022).

Important soil forming processes in Solontschak, Solonetz, and Solontschak-Solonetz include the enhanced process of shrinking and swelling (Nestroy et al., 2011), which arguably leads to better water permeability during hot and dry seasons (Krachler and Krachler, 2007), and an exchange of Sodium-humate (Franz and Husz, 1961). Furthermore, the soil is subject to stark seasonal variations in salt content, pH, and EC connected with groundwater and precipitation/evaporation dynamics (Ghobadian, 1966). Several authors mention high quantities of silicic acid due to alkalinity and subsequent weathering of silicates (Franz and Husz, 1961; Ghobadian, 1966; Krachler and Krachler, 2007). It is hypothesized that this silicic acid forms chemical compounds with sodium (Franz and Husz, 1961) or smectites and other clay minerals (Krachler and Krachler, 2007) which then reduce SHC and increase swelling/shrinking dynamics. Krachler and Krachler, 2007 also proposed the formation of (proto)dolomite, potentially with the help of microorganisms within the soil. They go as far as hypothesizing that an impermeable fine-grained soil (clay mineral and (proto)dolomite particles) was formed from an originally coarser-grained primary material. Furthermore, microbial activity in highly alkaline environments seems to be a key process in decreasing organic matter accumulation and subsequent sedimentation. This has been shown both by observations of microorganisms and DOC levels in soda pans (Kirschner, 2007) and by a sedimentation study comparing degraded and intact soda pans, which found that no sedimentation occurred in intact areas of Lange Lacke since the atomic bomb tests in the 1950s (Krachler and Krachler, 2007). It has also been hypothesized that anaerobic sulfate reduction might be a source of Na_2CO_3 (Ghobadian, 1966). Lastly, the Hungarian literature mentions the potential of feldspar weathering through alkalization potentially releasing Na^+ (Sümegi and Boros, 2013), this hypothesis however has not been reported in literature on Austrian soils.

1.4. Soda pans in Seewinkel

Soda pans (“Salzlacken”) in Austrian Seewinkel, are highly threatened landscape patches which in 1855 consisted of 139 distinct lakes covering an area of 3.615 ha. In 2012, only 59 of these lakes were still visible, of which 24 were already considered as “dried up” (Krachler et al., 2012). Soda pans are protected by the habitat directive of the European Union as habitat type 1530 “Pannonic salt steppes and salt marshes” (*Council Directive 2013/17/EU*. European Council, 2013). The Austrian Environment Agency further lists this habitat type as “particularly important” (Umweltbundesamt, 2019). Consequently, conservation and ideally rehabilitation of this habitat type is of high ecological importance.

1.4.1. Geomorphological origin of soda pans

The geomorphological origin of soda pans in the examination area is still subject to debate, and scientific consensus is lacking: Häusler, 2007 identified two different age groups of soda pans: The soda pans, which are directly east of Lake Neusiedl, can be seen as former parts of Lake Neusiedl and are approximately 1500 years old. Soda pans, which are located further to the east, are likely much older: Riedl, 1965 hypothesized that soda pans are a product of “pingos”, isolated ice bodies, which formed during the last Würm glaciation. Bernhauser, 1977 acknowledged the pingo theory for some soda pans, however, in his work, he stated that most soda pans were likely formed by sinking of sediments above the baserock through loss of connate water. Draganits et al., 2022 postulated that soda pans were formed by sinking through thermokarst during the Würm glaciation by comparing topographies of landforms in Seewinkel and Siberia, where recent thermokarst structures are found. Häusler, 2007 on the other hand, first postulated that soda pans might be a product of erosion (“erosion hypothesis”). The author links the formation of soda pan basins closely to a “saline horizon” (see below) within the lakebed. This hypothesis was further developed, whereby the origin of erosion is now located in the Riss/Würm interglacial through fluvial-limnic processes also found today at the Mackenzie river, Canada (Häusler, 2020). This was further supported by findings of ¹⁴C-dated plant material within sediments of soda pans that was dated during Würm glaciation (Häusler, 2023).

The Hungarian literature on formation of soda pans in the wider Pannonian basin recognizes that conditions for sodification were already present during Würm glaciation approximately 40.000 years ago, indicated by fossil soil records. This is supported by climate reconstruction showing that in this phase, average July temperatures already reached 17 – 20°C while average temperatures in January lay below -15°C in the basin area. For “Lake Fehér” at Kardoskút, Hungary, a fluvial origin is described, whereby 26.000 years ago the lake was detached from the fluvial system and sodification started approximately 16.000 years ago (Sümegei and Boros, 2013).

1.4.2. Geomorphological origin of a saline horizon

The origin of salt in Austrian soda pans is still subject to ongoing debate (Draganits et al., 2022): Due to a much larger extent of soda pans in Hungary it seems reasonable to first look upon theories of salt origins in the broader Pannonian basin. It must be mentioned, however, that saline soils and consequently soda pans in Austria are situated on the Western distribution border of non-coastal saline soils (Nestroy and Kuttner, 2022), therefore processes might be enhanced or different from more central areas of the distribution area as indicated in Husz, 1967. In their overview work, Sümegi and Boros, 2013 present several theories on salt origins in soda pans in the Pannonian basin²: Some theories emphasize erosion and/or mostly fluvial transport processes of saline material/salt from mountain ranges or Tertiary salt deposits within the Pannonian basin. Another theory states that through carbonate alkalization of groundwater, Na⁺ was increasingly dissolved from weathering feldspar minerals therefore at least some of the salt content might stem from weathering of Quaternary material. Lastly, seepage of deep groundwater into near-surface groundwater bodies is theorized to have led to the formation of saline soils wherever (saline) groundwater levels lay <2 m below surface and climate favored above-described salinization processes. However, the authors mention that conditions in the Pannonian basin represent a mosaic-like structure. Consequently, all theories might hold true for certain areas.

In Austria, the ascendance of (saline) deep groundwater into near-surface groundwater bodies has also been proposed by Fritsch and Tauber, 1959 and is followed by some publications (Bernhauser, 1977; Krachler et al., 2000; Zimmermann-Timm and Teubner, 2021). This “ascendence hypothesis” is criticized by a present day groundwater study in Seewinkel (Häusler, 2023). A more common explanation of salt origin is the primary deposition during an interglacial period. This period was likely warmer and more arid than today (Franz and Husz, 1961; Ghobadian, 1966; Häusler, 2023). Franz and Husz, 1961 hypothesize that a dried-out shallow lake in the present area of Seewinkel was responsible for the accumulation of salts and the formation of a sediment layer named “saline horizon”. In Häusler, 2020 and Häusler, 2023 the author argues that a combination of fluvial-limnic processes were responsible for the formation of a saline horizon through evaporation.

The underlying coarse sediments are dated in the Riss glacial maximum (Bernhauser, 1977; Franz and Husz, 1961) while the overlying sediments are dated in the Riss-Würm interglacial period (Franz and Husz, 1961). Therefore, it was argued that the saline horizon was also formed in the Riss-Würm interglacial period (Franz and Husz, 1961; Häusler, 2020; Häusler, 2023). Other works date the underlying sediments as much older and therefore the saline horizon would have been deposited in the Mindel-Riss interglacial (Fuchs, 1974; Häusler, 2007). This view is shared in the most recent pedological map of Seewinkel (Nestroy and Kuttner, 2022).

² Refer to Boros et al. (2013) for a full list of authors

1.4.3. Concept of hydrological functionality

Steiner, 2006 distinguished three main types of soda pans. Type one is split into two subtypes (1a and 1b) and comprises soda pans which are entirely dependent on precipitation for water input so-called “precipitation fed soda pans”. Nevertheless, groundwater levels are decisive whether subtype 1a or 1b is formed. This is due to the supposed link between the capillary rise of salts and the impermeability of the topsoil. If groundwater levels are permanently too low, subtype 1b forms from subtype 1a which fundamentally leads to degradation of the soda pan because of higher soil permeability and infrequent, lower water tables (Figure 10).

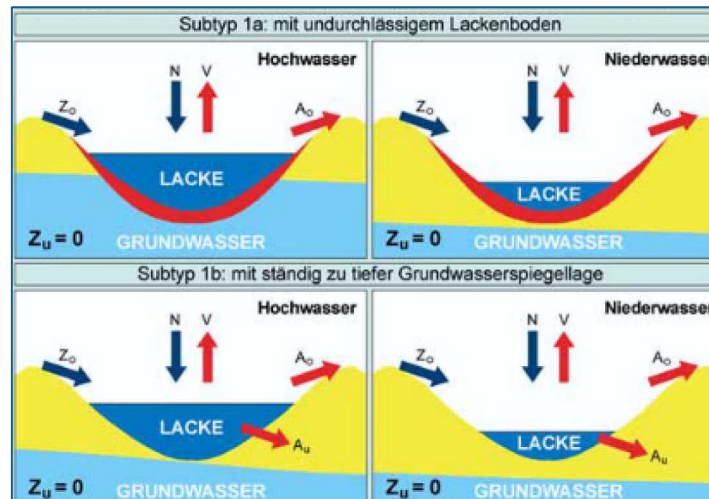


Figure 10: Type 1 soda pans under high groundwater (“Hochwasser”) and low groundwater (“Niederwasser”) conditions according to Steiner, 2006 p. 64.

Type two (2) comprises a mixed system of precipitation and groundwater feeding. During higher groundwater levels, groundwater can seep through permeable border areas, and it contributes to a free water table on the impermeable central saline layer. Type three (3) are entirely groundwater-fed lakes without an impermeable layer to accumulate precipitation (Figure 11).

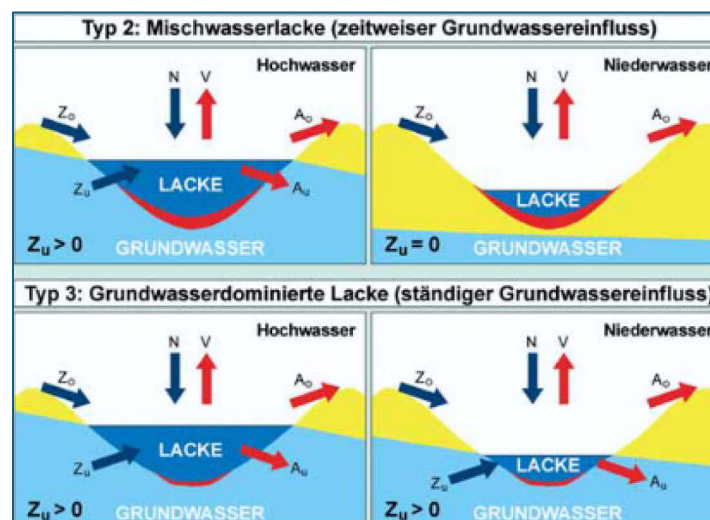


Figure 11: Type 2 and 3 soda pans under high groundwater (“Hochwasser”) and low groundwater (“Niederwasser”) conditions according to Steiner, 2006 p. 64.

In their concept, Krachler and Krachler, 2007 emphasized chemical parameters in combination with topsoil SHC (<15 cm) as main factors for “white water” soda pan functionality. “White water” soda pans exhibit a stable turbidity through most of the duration of a free water table. They hypothesized that these soda pans’ topsoil SHC naturally changes throughout the year depending on soil salt content and consequent shrinking and/or dispersion processes. Starting in autumn and winter, through rainfall and reduced evaporation, the soils in the lakebed start to expand and shrinkage cracks close. Consequently, SHC through preferential flow is reduced, and precipitation starts to accumulate due to low SHC and low evaporation. Due to the highest water tables in early spring, the soda pans’ free water tables exhibit the lowest salt concentrations, and therefore, SHC is further reduced due to dispersion processes. It is only in summer that, through evaporation, salt contents in the free water table increase and CTC is reached, whereby the lake water becomes clear (coagulation of particles), and shrinkage of the soil starts as early as a few centimeters of free water table are still present. As a result of autochthonous soil formation within soda pans (refer to chapter 1.3.6), the authors theorized that over time, soda pans are disconnected from direct groundwater influence on the free water tables and become entirely precipitation-fed. An analogue to type 3 lakes in above-mentioned concept are referred to as “black water” lakes, which are strongly influenced by groundwater and do not show stable turbidity or relatively high salt contents.

1.4.4. Sampled soda pans – description.

Table 3: Parameters of examined soda pans Martenhoflacke, Moschadolacke and Illmitzer Zicksee.

Soda pan	Martenhoflacke	Moschadolacke	Illmitzer Zicksee
Lakebed	6.9 ha	13.8 ha	206 ha
Lakebed diameter	1000 m	1380 m	12100 m
Reed area	0.9 ha	3.7 ha	87 ha
Other vegetation	2.3 ha	9.5 ha	65 ha
Human-caused structures	/	0.6 ha (depression)	/
Free water area	3.7 ha	0 ha	54 ha

1.4.4.1. Martenhoflacke

After the concept of Krachler and Krachler, 2007 the soda pan “Martenhoflacke” is a “white water” lake which can be likely classified as subtype 1a as defined by Steiner, 2006. The lake is reported not to have been influenced by groundwater since at least 1957, indicating a possible shift from a mixed type 2 lake. The lake exhibits a typical plant zonation towards the lake center, ranging from salt-tolerant grasses towards specialized halophytes. From a chemical perspective, low content in earth-alkali elements and a pH of approximately 9 in the topsoil down to 8.5 in the subsoil is reported. Martenhoflacke is likely endangered by low groundwater levels through trenches and an increase in vegetation (Krachler et al., 2012).

1.4.4.2. Moschadolacke

Moschadolacke is originally a “white water” lake, however it has been highly degraded, arguably due to low groundwater levels and high SHC (Krachler et al., 2012). Consequently, the lake can be seen as subtype 1b, lacking a (top-)soil layer of low permeability. The lake is mainly covered by a meadow, which, towards the center, turns into a dense reed belt. The center is comprised of an excavated depression which is used by hunters to attract water birds in autumn. Furthermore, a trench “Moschadograben” is directly located within the lake and drains surface water immediately. Consequently, the lake is degraded through the massive reduction of groundwater and through trenches which are directly draining surface water from the lake (Krachler et al., 2012). It is important to note that in 2021 “salt” [sic] was applied in the lake’s center as a measure to “save” the lake (WWF, n.d.).

1.4.4.3. Illmitzer Zicksee

This soda pan originally was one of the biggest soda pans in the area, exhibiting both a high salt content as well as groundwater influence. Consequently, the lake is likely of a type 2 mixed type. This is indicated on old maps showing a fully water-saturated Illmitzer Zicksee next to a dried-out Lake Neusiedl. Nevertheless, the lake has already been reduced strongly by a large reedbelt in 1959 and until 1980 wastewater was diverted into the lake (Krachler et al., 2012). Franz and Husz, 1961 stated that wide areas in the Illmitzer Zicksee were anthropogenically disturbed. Nowadays, Illmitzer Zicksee is endangered both by a massive increase of common reed (*Phragmites australis*) and other vegetation as well as extensive groundwater extraction and drainage for settlement safety. Illmitzer Zicksee is deemed unstable and measures have to be taken to stabilize the lake in the future (Krachler et al., 2012).

1.5. Research objectives

From the literature reviewed in this chapter, it becomes apparent that SHC in saline soils is a highly complex variable related to many soil parameters. Furthermore, the origin of both soda pans' landforms and saline soils, as well as the subsequent (geo)hydrology of soda pans in Seewinkel, is not fully understood yet. In this context, (low) SHC of saline soils are often implied in conceptual models regarding the development of free water tables. To the knowledge of the author however, little laboratory measurements of SHC (e.g. Ghobadian, 1966) and no in-field SHC measurements of soils in soda pans in Seewinkel have been published. Moreover, SHC of saline soil has not been examined in detail in relation to soil property measurements both within and between soda pans. Derived from water saturation and suspected degradation status, average SHC in the order Illmitzer Zicksee < Martenhoflacke < Moschadolacke is suspected. The following research questions and hypothesis are formulated:

How do SHC and soil properties vary between and within examined soda pans?

H1.1: SHC varies between all examined soda pans.

H1.2: Soil exchangeable and soluble cations as well as derived soil properties are the main drivers of SHC reductions in soils of Austrian soda pans.

H1.3: SHC in soda pans which did not dry out over the examination period is lower than SHC in soda pans which did dry out over the examination period.

H1.4: Lower SHC can be attributed to lower elevations within examined soda pan lakebeds.

2. Materials and methods

2.1. Study design, sampling and SHC measurements

Three soda pans, namely Martenhoflacke, Moschadolacke and Illmitzer Zicksee were chosen in cooperation with the national park “Neusiedler See – Seewinkel”. Selected lakes showed differences in hydrological behavior and general condition. In each soda pan, a transect from the visibly deducible highest point of the lakebed in the direction of the predetermined lowest point of the soda pan was set up. The transects encompassed five points of measurement. (Figure 1, Appendix Table 1). The other sampling locations were either placed equidistant from each other or they were selected according to visible changes in vegetation and/or elevation.

In-field measurements and sampling took place in August and early September of 2024. Three mixed topsoil samples, three soil cylinder samples and three “Pürckhauer” subsoil samples were taken. Furthermore, SHC measurements were performed at random in sampling areas around the points. In the case of Moschadolacke and Illmitzer Zicksee, measurements were performed randomized in a circle ($r = 3 \text{ m}$) around the sites. At Martenhoflacke, due to possible conflict with other scientific works, a half-circle ($r = 3 \text{ m}$) away from the conflicting sampling area was selected. The sampling depth of topsoil samples was selected at 8 – 12 cm deeper than the soil surface, which approximated the maximal depth of the infiltrometer within the soil. Mixed subsoil samples were taken with the Pürckhauer sampler in depths of 40 – 50 cm. In case of water-saturated areas, as was the case in Illmitzer Zicksee (point 1 and 2), a PE pipe was used as blockage to drain water from above the soil surface and retrieve topsoil and subsoil samples. At Ma4 and Ma5, no subsoil samples could be obtained due to hardness of soil and rough grain sizes, at Zi1 and Zi2, no soil cylinder samples were obtained due to water saturation and poor soil structure. All soil samples were then examined according to the following chapter 2.2.

The measurements of SHC were conducted according to ÖNORM B4222-2 (Österreichisches Normungsinstitut, 2002a) with a “Standrohr” single ring infiltrometer (Figure 12). After a saturation period of approximately eight hours, SHC was measured by differences in water table heights ($h_{\text{start}} - h_{\text{end}}$) in a measurement pipette with $r_M = 0.0055 \text{ m}$ ($r_0 = 0.0425 \text{ m}$) over a period of $<1 \text{ h}$ depending on SHC on respective measurement sites. Consequently, the measurements took place under falling pressure height. Water temperature before and after the procedure was measured and protocolled. If possible, high temperature differences during the procedure were avoided, however, due to the exposed position of the measurement points, this was not fully avoidable and needed to be corrected in the results. To conduct measurements, deionized water was used to simulate rainwater and to keep the conditions similar across all lakes. In case of two water-saturated positions (Zi1 and Zi2) this infiltrometer type could also be used, however EC values of infiltrating water were higher due to mixing of lake water with deionized water.



2.2. Measurement of soil properties

2.2.1. General preparation

To examine soil properties in the laboratory, an aliquot (app. 100 g) of the mixed topsoil samples and all Pürckhauer samples from 40 – 50 cm depth (wherever available) were air-dried at 40°C. Consequently, samples were ground and sieved through a 2 mm mesh. Soil cylinder samples were used to measure initial soil water content and dried at 105°C to obtain dry weight and consequently bulk density. For analysis that required fine-ground soil, an aliquot of air-dried, sieved soil was further ground to a fine powder utilizing a ball mill. Sample splitting was conducted according to ÖNORM L1060 (Österreichisches Normungsinstitut, 2004). For preparation of solutions, milli-Q ultrapure water was used, if not specified differently.

2.2.2. Soil pH (pH)

Analysis of soil pH-values were conducted following procedures in ÖNORM L1083 (Österreichisches Normungsinstitut, 2006) by using 6 g air-dried soil mixed with 30 mL 0.1M CaCl₂ solution as a suspending agent. After hand-shaking, samples were placed in an overhead shaker for 2h and consequently pH-values were measured using a digital glass Ag+/AgCl electrode over a period of 20 min until stable values.

2.2.3. Soil electrical conductivity (EC)

Electrical conductivity was measured in a 2:3 soil-water extract due to difficulties in obtaining enough extract from the saturation paste. The mixture was shaken carefully by hand and left overnight. The next day, measurements of EC(2:3) values were conducted using a standard EC-meter with temperature correction. To determine a theoretical EC_e (EC from saturation extract), which was necessary for improved soil classification according to the Austrian classification of saline soils, the method described in WRB after the FAO description was used (IUSS Working Group WRB, 2022). The method implies a linear correlation of EC and dilution ratio, whereby the dilution ratio in the saturation paste is estimated by classifying the soil texture according to WRB and comparing the classified soil texture to organic carbon content. This yields a theoretical water content in the saturation paste (WC_e), which can be used to convert EC(2:3) to EC_e (Figure 13; for WC_e calculation refer to IUSS Working Group WRB, 2022, p. 203). Since the resulting EC_e-values are an estimate of actual EC_e, this variable was only used for soil type classification. In the following work, EC is used synonymously with EC(2:3) if not specified differently.

$$EC_e = EC(2:3) * \frac{3}{2} * \frac{100}{WC_e}$$

Figure 13: Calculation of EC_e from EC(2:3) values.

2.2.4. Soil texture (clay%, silt%, sand%)

Soil texture measurements were conducted according to ÖNORM L 1061-2 (Österreichisches Normungsinstitut, 2002c), utilizing 10g (topsoil) and 5g (subsoil) of air-dried and sieved (<2mm) fine soil samples. Soil samples were mixed with 25 mL (12,5 mL in case of subsoil samples) 0.1M Tetrasodium pyrophosphate ($\text{Na}_4\text{P}_2\text{O}_7$) dispersion agent and left for 8h, followed by a 6h shaking period in approximately 100 mL of water. The suspension was then transferred onto a 0.063 mm sieve and washed with deionized water to remove sand particles (>0.063 mm), which were then moved to a vessel and dried at 105°C and measured gravimetrically. The remaining suspension was transferred to a 1 L measurement cylinder and diluted with deionized water up to the 1 L mark. After stirring, the suspension was left at 21°C for a pre-defined time (3 h 46 min and 53 s) according to Stokes' law for larger particles to settle down. Consequently, a 20mL pipette was utilized to remove the remaining particles from a depth of 5cm below the water level of the measurement cylinder. This aliquot only contained particles <2µm (clay) and was used to calculate the total clay content floating within the 1 L suspension as follows: The retrieved 20 mL suspension was moved to a vessel, dried at 105°C and gravimetrically measured. Furthermore, both the weight of the suspending agent and the calculated minimal salt content (see chapter 2.2.6) were subtracted from the mass of clay particles in the suspension and the resulting clay mass from 20mL of suspension was multiplied by 50 (Figure 14). Silt particle mass was then obtained by subtracting sand and clay masses from 10g/5g respectively. For the comparison of measurement sites, relative masses of sand, silt and clay were then calculated (sand%, silt%, clay%).

$$m_{\text{clay}} = (m_{20\text{mL dry}} - m_{\text{Na}_4\text{P}_2\text{O}_7} - m_{\text{saltmin}}) * 50$$

Figure 14: Calculation of clay mass from a 20 mL suspension aliquot

2.2.5. Soil exchangeable cations and effective Cation Exchange Capacity (CEC_{eff})

Soil-bound cations were determined according to ÖNORM L1086-1 (Österreichisches Normungsinstitut, 2001). First 2.5 g of air-dried soil were mixed with 50 mL 0.1M BaCl_2 extract solution and left overnight. After an additional 2h of shaking the suspension was then transferred on a 589 black ribbon paper filter. To obtain remaining cations on the shaking vessel and on the filter paper, an additional 50 mL of 0.005M BaCl_2 solution followed by 50 mL of water were used. The BaCl_2 extract was then diluted with 2% nitric acid (HNO_3) to ratios of 1:10, 1:100 and 1:1000 and Na^+ , K^+ , Mg^{2+} as well as Ca^{2+} concentrations were quantified using Atomic Emission Spectroscopy on an AAnalyst 200 (PerkinElmer) (calibration slopes: Appendix 11 - Appendix 14). CEC_{eff} was then estimated as the sum of measured cations. Due to unit (mmol/kg or meq/kg) differences between the Austrian ÖNORM L1086-1 and the international WRB (IUSS Working Group WRB, 2022), all values both for mmol/kg and meq/kg as well as $\text{CEC}_{\text{eff, AT}}$ (ÖNORM) and $\text{CEC}_{\text{eff, INT}}$ (WRB) were calculated. Furthermore, the indices SAR and CROSS could be derived (Figure 9). An overview

of measured and calculated variables is depicted in Table 4. An exemplary calculation of Na(mol%) and Na(meq%) is given in Figure 15.

Table 4: Overview of exchangeable cation derived variables and abbreviations

Variables	Derivations for each basic cation			
	Na ⁺	K ⁺	Mg ²⁺	Ca ²⁺
Molar content [mmol/kg fine soil]	Na(mmol)	K(mmol)	Mg(mmol)	Ca(mmol)
Molar sum of basic cations [mmol/kg fine soil]	CEC _{eff, AT}			
Molar cation saturation [mol-%]	Na(mol%)	K(mol%)	Mg(mol%)	Ca(mol%)
Milliequivalent content [meq/kg fine soil]	Na(meq)	K(meq)	Mg(meq)	Ca(meq)
Mols of charge sum of basic cations [meq/kg fine soil]	CEC _{eff, INT}			
Milliequivalent cation saturation [meq-%]	Na(meq%)	K(meq%)	Mg(meq%)	Ca(meq%)
Sodium Absorption Ratio	SAR			
Cation Ratio of Soil Structural Stability	CROSS			

$$Na(mol\%) = \frac{Na(mmol)}{CEC_{eff, AT}}$$

$$Na(meq\%) = \frac{Na(meq)}{CEC_{eff, INT}}$$

Figure 15: Calculation of molar and mols of charge cation saturation for Na⁺

2.2.6. Soil soluble cations and soil soluble salt content (saltmin)

Soil soluble cations were determined according to the above-described procedure, however, without the addition of a BaCl₂ solution to the milli-Q water. Due to the highly dispersive behavior of the soil, an additional filtration step through nylon syringe filters (0.45 µm) had to be performed to obtain a clear water extract of the soil. Atomic emission spectroscopy measurements were again conducted utilizing an AAnalyst 200 (PerkinElmer), with dilution ratios as defined above.

To obtain the weight of soil soluble salts, first, it was attempted to weigh the dry salt content of 10 mL clear water extract. This, however, failed due to low dissolved salt weights (0.0001 g – 0.001 g for most samples). Therefore, the cation weight measured in the water extract by flame AES as well as a minimum counterion weight for 1 kg of fine soil was calculated: Within examined soda pans possible anions include Cl⁻, HCO₃⁻, CO₃²⁻ and SO₄²⁻ (Krachler et al., 2012). For Na⁺, halite (NaCl) was identified in all three soda pans as one of the dominant soluble salts, while K⁺ ions were detected from sylvine (KCl) in Illmitzer Zicksee, in both Moschadolacke and Martenhoflacke no potassium containing minerals were found (Csaplovics et al., 2018). Both halite and sylvine possess the lowest possible molar weight for monovalent cations of all minerals found within soda pans that contain Na⁺ and K⁺. Therefore, Cl⁻ was chosen as a counterion for the calculation of both Na⁺ and K⁺ minimal salt weight. Furthermore, in

Illmitzer Zicksee, no mineral containing Mg^{2+} and only on some measurement sites anhydrite ($CaSO_4$) as a possible source for soluble Ca^{2+} was detected. In Martenhoflacke, no minerals containing Mg^{2+} or Ca^{2+} were observed, and Moschadolacke only contained low quantities of northupite, a Mg^{2+} containing mineral ($Na_3Mg(CO_3)_2Cl$) in the evaporation residuals (Csaplovics et al., 2018). Although both $CaCO_3$ and $MgCO_3$ are of very low solubility, due to expectable high amounts in all soda pans and the relatively low molar mass of carbonate, CO_3^{2-} was chosen as a counter anion for a minimum estimate of Mg^{2+} and Ca^{2+} soil soluble salts. Table 5 gives an overview of variable abbreviations, Figure 16 shows the calculation procedure for the minimal relative salt content in the fine soil ($salt_{min}\%$).

Table 5: Overview of soil soluble cation derived variables and abbreviations

Variables	Abbreviations for each basic cation			
	Na^+	K^+	Mg^{2+}	Ca^{2+}
Soluble cation absolute content [mmol/kg soil]	$Na(H_2O)$	$K(H_2O)$	$Mg(H_2O)$	$Ca(H_2O)$
Soluble cations relative content [mol-%]	$Na(H_2O\%)$	$K(H_2O\%)$	$Mg(H_2O\%)$	$Ca(H_2O\%)$
Relative salt content – fine soil [wt. %]	$salt_{min}\%$			

$$n(Cl^-) = Na(H_2O) + K(H_2O)$$

$$n(CO_3^{2-}) = Mg(H_2O) + Ca(H_2O)$$

$$m(salts Na^+, K^+) = M(Na^+) * Na(H_2O) + M(K^+) * K(H_2O) + n(Cl^-) * M(Cl^-)$$

$$m(salts Mg^{2+}, Ca^{2+}) = M(Mg^{2+}) * Mg(H_2O) + M(Ca^{2+}) * Ca(H_2O) + n(CO_3^{2-}) * M(CO_3^{2-})$$

$$m(minimal\ salt\ content) = m(salts Na^+, K^+) + m(salts Mg^{2+}, Ca^{2+})$$

$$salt_{min}\% = \frac{m(minimal\ salt\ content)}{1\ kg\ fine\ soil}$$

Figure 16: Calculation of $salt_{min}\%$

2.2.7. Organic (OC%), inorganic carbon (IC%) and Carbonate content (Carb%)

To determine organic (OC%) and inorganic carbon (IC%) 0.0010 – 0.0015 g of ground-down air-dried fine soil was dry burned and analyzed in a Leco “RC612 Multiphase Determination of Carbon and Water”. Usually, two repetitions were measured for each soil sample; in cases of differences (>1%), a third measurement was conducted to get a better estimate of OC%/IC%. Since CO_3^{2-} was expected to contain most of the inorganic carbon within the soil, measured IC% was directly transformed into carbonate content (Carb%) by multiplying IC% with the ratio of respective molar masses ($\text{CO}_3^{2-} : \text{C}$).

2.2.8. X-Ray diffraction

The mineralogical composition of the samples was determined using X-ray diffraction (XRD). The powdered bulk samples were pressed into sample holders and analyzed using a Panalytical X'Pert PRO X-ray diffractometer ($\text{CuK}\alpha$ radiation, 40 kV, 40 mA, step size 0.0167, 5 s per step). The interpretation was carried out with the programs X'Pert Data Viewer and X'Pert HighScore Plus.

Additionally, the clay mineralogy of the soda pans was analyzed for points Ma1, Mo1, and Zi1, both for the upper and lower soil. To separate the clay minerals, approximately 15-20g of air-dried sample were mixed with 150 mL of 15% H_2O_2 solution to destroy organic matter. After completion of the reaction, the suspensions were dispersed with a 400 W ultrasonic rod for 3 min. The $<2\ \mu\text{m}$ fraction was then separated using sedimentation in Atterberg cylinders (24h 33min at 21°C). The clay fraction was air-dried at 40°C . Subsequently, 50 mg of sample was mixed with 50mL 1M MgCl_2 and 1 M KCl solution, respectively. After one day in an overhead shaker the samples were washed with deionized water using a centrifuge. Following the washing procedure, both Mg^{2+} - and K^+ -saturated samples were resuspended in 5mL deionized water and 1 ml of the suspension (10mg/ml) was pipetted onto a glass slide. The oriented, K- and Mg-saturated samples were analyzed in air-dried state and after vapor solvation with either ethylene glycol (KEG) or glycerol (MgGly) at 60°C for 24 h to identify expandable clay minerals like smectite. Additional K-saturated samples were heated to 550°C to destroy kaolinite and expandable clay minerals (Moore and Reynolds, 1997).

The evaluation was carried out using the Data Viewer program based on the d-value positions according to Moore and Reynolds, 1997.

2.2.9. Soil water content (WC), bulk density (BD) and soil particles >2 mm (>2mm%)

Soil water content (WC) of topsoils at the sampling points was measured by weighing undisturbed soil samples taken by sampling cylinders (diameter 57 mm; height 40,5 mm) before and after drying at 105°C and calculating relative water content. Consequently, bulk density (BD) was calculated by dividing dry soil weight with the volume of sampling cylinders (100 cm³).

Soil particles >2 mm could only be estimated from mixed samples since large amounts of sample are necessary to receive good estimates of bigger particles within soils (Österreichisches Normungsinstitut, 2002b). For topsoil samples, aliquots of air-dry soil samples were air-dried, weighed and sieved through a 2mm mesh. Since limited quantities were available for subsoils the whole air-dried sample was weighed and dry-sieved through a 2 mm mesh. The >2 mm fraction was then weighed and related to sample mass before sieving through a 2 mm mesh.

2.3. Further environmental and calculated parameters

Next to sampling and in-situ measurements two environmental parameters were gathered: Fully closed plant cover at the examination site was noted visually in a binary, subjective “yes” (P_{cov}) or “no” (P_{uncov}) variable. Appendix 1 to Appendix 10 show examples for P_{cov} and P_{uncov} sites. Furthermore, observations of soil shrinkage cracks at least throughout September 2024 were planned on P_{uncov} saline soil sites, however observations ended abruptly after heavy rainfall in the mid of September 2024. Even though no quantitative measures of soil cracks were gathered saline soil sites particularly at Ma2, Zi3 and Zi4 could be compared in their formation of shrinkage cracks due to similar topsoil WC at the time of measurement.

2.4. Data analysis and interpretation

2.4.1. Calculation of raw k_f -values

To calculate raw k_f -values, the formula for a falling pressure head according to Österreichisches Normungsinstitut, 2002a was used. The parameters f and F were set to $f = 2$ for a measurement cylinder depth of $<4r_0$ and $F = 2,5$ for an infiltrometer with a circular test area. To obtain the flow potential h_G , a sum of hydraulic pressure height and the difference of potential between the soil and groundwater surface Δh was calculated. According to Österreichisches Normungsinstitut, 2002a, this formula shall only be used for groundwater table depths of >2 m, however, groundwater table depths >1 m could not be determined with the devices used in this study. Consequently, Δh was estimated with the formula for groundwater table depths >2 m. Figure 17 shows the calculation of raw k_f values, as well as variables h_G and Δh . Appendix Table 2 gives an overview on measured and derived variables.

$$k_{f,raw} = \frac{f * F * r_m^2}{\Delta t * 4 * r_0} * \ln \frac{h_{G,start}}{h_{G,end}}$$

$$h_{G,start/end} = h_{G,start/end} + \Delta h$$

$$\Delta h_{start/end} = 0.683 * \sqrt{h_{start/end} * r_0}$$

Figure 17: Calculation of k_f and co-variables.

2.4.2. Correction of raw k_f -values

Raw k_f -values had to be corrected because of the dependency of k_f on the viscosity of the examination liquid and, therefore, on the temperature of the distilled water used to measure k_f -values. Furthermore, due to temperature differences during measurements, a second pre-viscosity correction step due to temperature-induced density changes in water and consequent volume changes had to be conducted.

For the density change correction, a linear temperature change between temperature measurements before (T_{start}) and after all measurements (T_{end}), as well as a homogeneous temperature within the infiltrometer, was assumed. Furthermore, only the volume change of water within the measurement cylinder was considered, and atmospheric pressure was set uniformly to 1000 hPa.

Using the equation derived from Abascal and Vega, 2005 for liquid water at 1000 hPa (Figure 18), densities at any given temperature could be obtained assuming isobaric conditions. Consequently, volume changes during the measurement period were calculated for each SHC measurement, and temperature-induced volume changes were subtracted from h_{end} .

$$\delta_{water}(T) = 3.05 + \frac{-3873.33}{T} + \frac{2.60 * 10^6}{T^2} + \frac{-8.24 * 10^4}{T^3} + \frac{1.28 * 10^{11}}{T^4} + \frac{-7.91 * 10^{12}}{T^5}$$

Figure 18: Approximation of water density of the liquid phase at 1000 hPa after Abascal and Vega, 2005

The temperature-induced volume changes were particularly observable at very low permeabilities (e.g. site Ma1, Appendix Table 3), inducing “negative” k_f -values. After temperature correction, some measurements yielded positive k_f -values. However, some measurements still yielded a negative result. Values that were still negative or 0 even after density correction were set to $k_f = 10^{-10}$ m/s (very low permeability) mainly for reasons of data transformation. Positive results were then viscosity corrected to $T = 10^\circ\text{C}$ ($k_{f\ 10^\circ\text{C, corr}}$) using the factor resulting from the equation presented in Österreichisches Normungsinstitut, 2002a by using the average temperature T_{av} (Eq. X).

$$\alpha(T_{av}) = \frac{1.359}{1 + 0.0337 * T_{av} + 0.00022 * T_{av}^2}$$

$$T_{av} = \frac{T_{start} + T_{end}}{2}$$

Figure 19: Calculation of the viscosity correction factor for a given temperature after Österreichisches Normungsinstitut, 2002a

To exclude large data variability in $k_{f\ 10^\circ\text{C, corr}}$, the suggested methodology according to Österreichisches Normungsinstitut, 2002a was adjusted in a way that only the three numerically closest measurements (lowest standard deviation) were used in calculating a mean k_f value for one measurement point (e.g. Ma1 – M1) or in statistical comparisons of sampled soda pans. Numerical results of relevant co-variables and all SHC measurements are shown in Appendix Table 3.

2.4.3. Statistics and transformations – k_f values and soil properties

To analyze differences in SHC between all three soda pans, as well as differences between individual soda pans, the Kruskal-Wallis rank sum test, as well as permutational ANOVA (PERMANOVA), based on Euclidean distance and ten thousand permutations were utilized. This procedure was also used for an overall test on closed plant cover (P_{cov}/P_{uncov}) and all measured k_f , 10°C , $_{corr}$ values. Due to the logarithmical nature and calculation (see above) of k_f , all statistical tests and correlations were conducted using a natural logarithmic transformation of k_f , 10°C , $_{corr}$. The necessity of this transformation is also indicated in the literature (Bagarello et al., 2006). Consequently, k_f 10°C , $_{corr}$ (m/s) is simply called SHC in both the result and discussion section if not specified differently.

Before analyzing soil properties, most variables were transformed, whereby percentages were transformed using the logit formula (Appendix 15) and other variables were generally transformed utilizing the natural logarithm of the data to reduce the effect of outliers and improve data distribution. Transformations excluded only pH (already logarithmic), >2 mm% (including zeros), and Bulk Density (minor variation).

To get an overview of the soil properties measured and calculated in this study, principal component analysis (PCA) was conducted for measured and calculated soil properties to determine patterns and redundant variables. Soil properties that were not analyzed in the PCA were SHC (directly related to PC values and tested separately), BD and WC (both missing for Zi1 and Zi2), as well as ion(mmol) and Carb% (both redundant because they are linearly related to ion(meq) and IC% respectively). Consequently, principal components (PC) accounting for $\approx 85\%$ of variability were analyzed in detail by r and R^2 and their statistical significance in correlation with soil properties. Furthermore, correlations between soil properties and SHC, as well as SHC and PC values were explored utilizing Ordinary Least Squares (OLS) regressions and their Pearson's r and consequently, R^2 . Moreover, a permutational test for statistical significance ($n=10000$) of correlations was performed. For the permutational test, the R package PermCor was used (Fang et al., 2024). An overview of terms used for statistical significance levels and correlation strengths is given in Table 6.

Table 6: Overview on correlation and significance levels used in this study

Correlation level	R^2
Strong correlation	$R^2 \geq 0.55$
Moderate correlation	$0.35 \leq R^2 < 0.55$
Weak correlation	$R^2 < 0.35$
Significance level	p
High statistical significance	$p \leq 0.05$
Medium statistical significance	$0.05 < p \leq 0.1$
No statistical significance	$p > 0.1$

2.5. Methodological constraints

2.5.1. SHC measurements

SHC measurements were constrained by several factors: As described in chapter 1.2, the assumption that soil is homogenous and therefore flow occurs with similar resistance in all directions is likely not met within saline soil, which may include layers of different texture through fluvial origins. To detect anisotropic flow, Österreichisches Normungsinstitut, 2002a recommends digging a soil profile on an initial soil wetting site and examining the wetting horizons within the soil. This, however, was not possible due to the high sensibility of most sampling sites.

Secondly, measurements were conducted with deionized water which affects soil stability which in theory can be maintained by increasing EC values to the CTC of the soil. This however poses several difficulties, namely logistical difficulties due to required extensive laboratory measurements after soil sampling but before SHC measurements. Furthermore, it remains unclear which EC values infiltration water really exhibits, because both Martenhoflacke and Moschadolacke did not possess open water tables during the measurement period. Furthermore, the EC of infiltration water is likely to change due to evaporation processes and pH levels vary with contents of HCO_3^- , CO_3^{2-} and SO_4^{2-} . Consequently, deionized water was used, which likely leads to soil dispersion but gives a reasonable estimate of rainwater infiltration across all soda pans.

Lastly, SHC measurements had to be conducted within a specific time, not only because of logistical constraints but also because of difficulties in temperature control. Consequently, some measurement sites which exhibited extremely low SHC (e.g., Ma1) would need long measurements under constant water temperatures to estimate exact k_f values $<10^{-10}$.

2.5.2. SHC correction

After SHC measurements, values had to be corrected in several ways: First, the flow potential, taking the influence of groundwater into account, had to be calculated. With the applied in-field measurements, however, no groundwater could be detected in depths $<1\text{m}$. According to Österreichisches Normungsinstitut, 2002a, groundwater influence until depths $<2\text{m}$ is determined by an approximation procedure. From groundwater table depths $>2\text{m}$, an estimation formula can be used. Due to unavailable groundwater table depth data in depths 1 m – 2 m the formula as shown in Figure 17 was used for all sites to give an estimate of groundwater influence.

Secondly, k_f values were corrected for water volume changes due to temperature by utilizing the formula proposed in Abascal and Vega, 2005. Water temperature used as input for this formula was measured before and after the SHC measurement series (Appendix Table 3), due to missing instrumental capacities for exact temperature measurements of infiltration water. Consequently, some sites that showed negative values before the density correction still showed negative values after the correction procedure. This is likely caused by non-linear temperature changes during

measurements or by differences in calculated densities for pressures of 1000 hPa and actual densities at the time of measurement. Table 7 gives an overview of calculated and measured water densities at 1000 hPa. Since this effect has not been anticipated, air pressures were not noted during SHC measurements and therefore 1000 hPa were assumed, ignoring potential pressure differences between measurements. Negative k_f values after density correction were set to 10^{-10} , to simulate very low permeabilities on these sites for data transformation and statistical calculation purposes.

Table 7: Difference between calculated and measured densities of water at relevant measurement temperatures and 1000 hPa (National Institute of Standards and Technology, 2025).

Temperature	Calculated water density (1000 hPa) [g/cm ³]	Measured water density (1000 hPa) [g/cm ³]
15°C	0.9996	0.9991
20°C	0.9987	0.9982
25°C	0.9974	0.9971
30°C	0.9958	0.9957
35°C	0.9940	0.9940
40°C	0.9922	0.9920

Lastly, k_f values were corrected for viscosity (Figure 19) whereby the average temperature T_{av} of T_{start} and T_{end} was used. This procedure also implied a linear temperature change between temperature measurements.

2.5.3. Correction of soil texture and salt content

Soil texture measurements were conducted by wet sieving of the sand fraction 0.2 – 2mm followed by the procedure described in chapter 2.2.4. In the case of this study, volumes removed by pipette after a specified time, which in theory almost exclusively contain clay fraction particles ($<0.2 \mu\text{m}$), may contain ions in higher quantities as well. This leads to an overestimation of gravitationally measured clay fractions. Consequently, salt mass must be removed physically or at least subtracted after raw m_{clay} measurements (Figure 14). In this study, no soluble anion contents were measured. Consequently, only contents of soluble basic cation within the soil were available. To obtain a minimum estimate of salt content for each site, $\text{salt}_{min}\%$ was calculated using the expected counterions with lowest molecular weight (refer to chapter 2.2.6). The resulting minimal salt contents in pipette volumes were then subtracted from clay mass to obtain a corrected clay% and subsequent silt% for all sites. Due to possible higher salt masses, clay% and silt% calculated within this study are constrained.

3. Results

3.1. Measurement results and evaluation: SHC

Measured SHC on average yielded low to very low permeabilities across all lakebeds. Singular measurements ranged from “normal” to “very low” permeability and were predominantly comparable to “clay-dominated” soils (refer to Table 1 – Table 2). Lowest SHC was measured in central, unvegetated Martenhoflacke (Ma1) where in two measurements on average no permeability was detected ($k_f \leq 0$, set to 10^{-10} m/s). Measured SHC/ k_f 10°C , corr in this soda pan ranged from 7.94×10^{-10} to 3.63×10^{-6} m/s (mean: 9.12×10^{-9} m/s). In Moschadolacke SHC/ k_f 10°C , corr ranged from 2.75×10^{-9} to 4.57×10^{-6} m/s (mean: 4.26×10^{-7} m/s), while Illmitzer Zicksee yielded values ranging from 6.76×10^{-9} to 2.69×10^{-7} m/s (mean: 2.04×10^{-8} m/s). Table 8 and Table 9 show the numerical results in log(m/s) and summary statistics for SHC (k_f 10°C , corr), Figure 20 depicts results of k_f 10°C , corr graphically.

Table 8: Results of k_f 10°C , corr measurements (M1, M2, M3) and plant cover status on each measurement site.

site	P _{cov}	M1	M2	M3	site	P _{cov}	M1	M2	M3	site	P _{cov}	M1	M2	M3
		k_f 10°C , corr [log (m/s)]					k_f 10°C , corr [log (m/s)]					k_f 10°C , corr [log (m/s)]		
Ma1	No	-10.00 ³	-10.00 ³	-8.75	Mo1	No	-8.26	-8.29	-8.56	Zi1	No	-8.00	NA	NA
Ma2	No	-9.11	-8.85	-8.77	Mo2	Yes	-5.63	-5.34	-5.71	Zi2	No	-7.73	NA	NA
Ma3	No	-8.10	-8.63	-8.92	Mo3	Yes	-5.87	-7.42	-6.51	Zi3	No	-7.57	-7.67	-7.84
Ma4	Yes	-7.31	-7.01	-6.41	Mo4	Yes	-7.24	-7.30	-6.33	Zi4	No	-7.54	-7.96	-7.73
Ma5	Yes	-7.22	-6.05	-5.44	Mo5	Yes	-6.05	-6.57	-5.86	Zi5	Yes	-7.76	-8.17	-6.57

Table 9: Summary statistics results of k_f 10°C , corr in all examined soda pans.

k_f summary statistics [m/s]	Martenhoflacke	Moschadolacke	Illmitzer Zicksee
n	15	15	11
min	10^{-10}	2.75×10^{-9}	6.76×10^{-9}
max	3.63×10^{-6}	4.57×10^{-6}	2.69×10^{-7}
mean	9.12×10^{-9}	4.26×10^{-7}	2.04×10^{-8}
median	2.34×10^{-9}	3.09×10^{-7}	1.86×10^{-8}
p _{25%}	1.20×10^{-9}	3.80×10^{-8}	1.10×10^{-8}
p _{75%}	9.77×10^{-8}	1.38×10^{-6}	2.69×10^{-8}

³ Values set to k_f 10°C , corr = 10^{-10} m/s because no SHC could be detected on this site

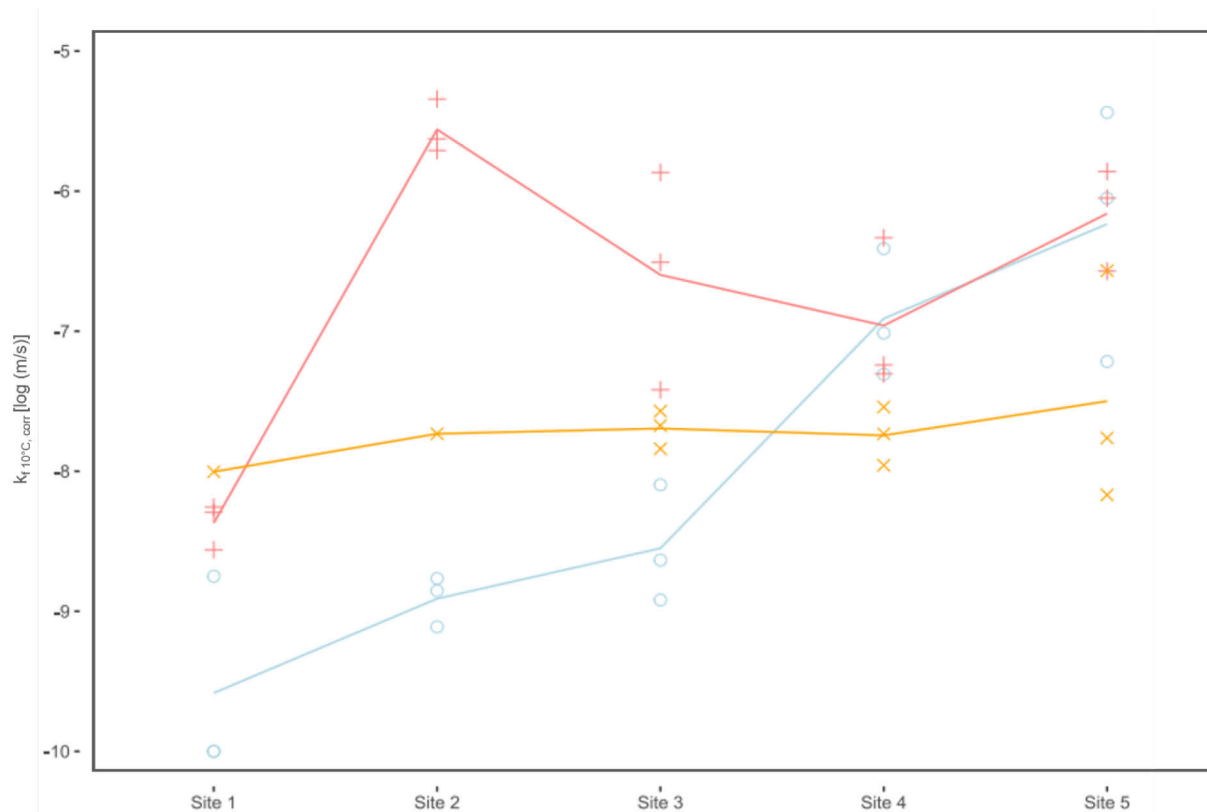


Figure 20: SHC measurement results in each soda pans' measurement site (blue: Martenhoflacke, red: Moschadolacke, yellow: Illmitzer Zicksee)

Within soda pans, a clear trend along the measurement transect was only visible in Martenhoflacke, where SHC was lowest in central parts of the lakebed and increased almost exponentially towards the edge of the lake. Illmitzer Zicksee showed no visible trend within the lakebed and the lowest standard deviation. The (flooded, singular) central measurements at Zi1 and Zi2 were both in a range measured at all other sites. Due to relatively high SHC at M3 in Zi5, the average SHC is highest on the edge of the lake, both M1 and M2 at Zi5 followed the trend of low deviation from the mean within this lake. In Moschadolacke, SHC on average was lowest at the only P_{uncov} site in the center at Mo1 (Appendix 7) and highest in the reed belt around the center (Mo2, Appendix 8). The lake revealed no clear trend in measurements at sites Mo3 – Mo5. Comparing the results of each site across all soda pans revealed the highest average SHC among sites within the vegetated areas of Moschadolacke (Mo2 – Mo5). SHC on average was lowest in the center of Martenhoflacke (Ma1 – Ma2), which was approximately ten times lower than in central Illmitzer Zicksee (Zi1 – Zi2). Measurement results towards the edge of the lake are comparable for both Martenhoflacke and Moschadolacke (Sites 4 and 5), which were part of plant-covered sites.

Overall statistical analysis of SHC across soda pans yielded significant differences $p < 0.05$. However, pairwise testing only revealed higher average SHC in Moschadolacke than in Martenhoflacke and Illmitzer Zicksee. Although not statistically significant, the overall average SHC was lowest in Martenhoflacke. Summaries of the results of comparing all soda pans and respective pairwise tests are given in Table 10 – Table 12.

Table 10: Statistical results of comparing SHC in all soda pans

Soda pans – SHC comparison			
Kruskal-Wallis test		PERMANOVA (n = 10000)	
H (χ^2)	8.929	F	5.782
p	0.012	p	0.001***

Table 11: Statistical results of pairwise comparison of SHC (Kruskal-Wallis test)

Pairwise Kruskal-Wallis test	Martenhoflacke	Moschadolacke	Illmitzer Zicksee
Martenhoflacke		H = 6.72	H = 0.9219
Moschadolacke	p = 0.010***		H = 5.576
Illmitzer Zicksee	p = 0.337	p = 0.018***	

Table 12: Statistical results of pairwise comparison of SHC (PERMANOVA, n = 10 000)

Pairwise PERMANOVA (n = 10 000)	Martenhoflacke	Moschadolacke	Illmitzer Zicksee
Martenhoflacke		F = 8.382	F = 0.6474
Moschadolacke	p = 0.010***		F = 8.063
Illmitzer Zicksee	p = 0.42	p = 0.010***	

Lastly, comparing mean SHC on P_{uncov} and P_{cov} sites revealed statistically lower mean SHC for P_{uncov} (3.89×10^{-9} m/s) than P_{cov} (2.75×10^{-7} m/s) status. Tables 13 and Figure 21 depict plant cover status and SHC comparison results.

Tables 13: Comparison of SHC for plant cover status, summary statistics and statistical test results and comparison of SHC

k_f summary statistics [m/s]	P_{uncov}	P_{cov}
n	20	21
min	10^{-10}	6.76×10^{-9}
max	2.88×10^{-8}	4.57×10^{-6}
mean	3.89×10^{-9}	2.75×10^{-7}
median	5.37×10^{-9}	3.09×10^{-7}
p _{25%}	1.48×10^{-9}	5.37×10^{-8}
p _{75%}	1.74×10^{-8}	1.38×10^{-6}

$P_{\text{uncov}}/P_{\text{cov}}$ – SHC comparison			
Kruskal-Wallis		PERMANOVA (n = 10000)	
H (χ^2)	10.5	F	59.84
p	0.001***	p	0.001***

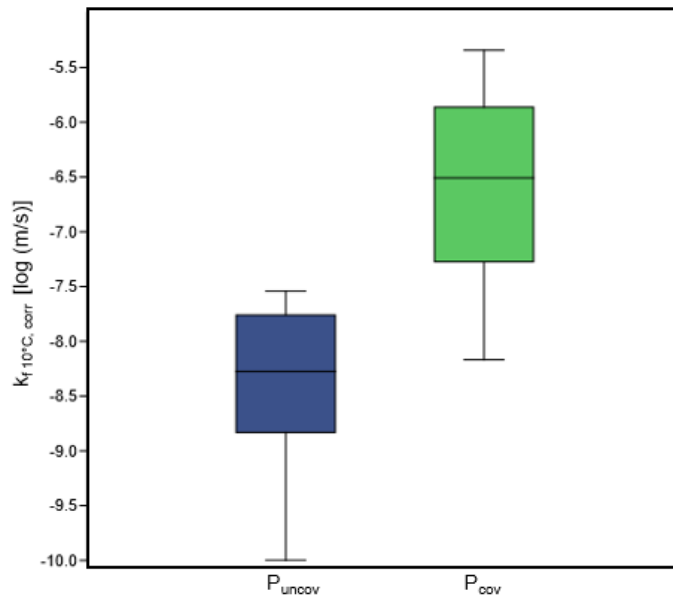


Figure 21: Plant cover status and $k_f 10^\circ\text{C}, \text{corr}$ results.

3.2. Measurement results: Soil properties

3.2.1. pH and electrical conductivity (EC)

Measurements of pH and EC resulted in highest values in central subsoils at Illmitzer Zicksee (pH >9, EC >2000 $\mu\text{S}/\text{cm}$). Water-saturated and recently water-saturated central positions at Illmitzer Zicksee showed comparable pH values in the topsoil than in Martenhoflacke (pH $\approx$ 8.7). EC values remained approximately 50% higher in the topsoil of central Illmitzer Zicksee (EC >1000 $\mu\text{S}/\text{cm}$) than in topsoils at central Martenhoflacke (EC $\approx$ 700 $\mu\text{S}/\text{cm}$). At Zi4, a position less influenced by free water tables, pH rose to its topsoil maximum of 8.95 and EC to 2180 $\mu\text{S}/\text{cm}$. At Moschadolacke EC and pH were increased although not as high as expected for a soda pan, consequently, overall pH and EC were lowest in this soda pan both for top- and subsoil. Nevertheless, the lowest pH was measured in the topsoil on the edge of Martenhoflacke, where pH almost showed neutral conditions (pH $\approx$ 7.63). In general pH was lowest on P_{cov} sites. Table 14 and Table 15 show the results of pH and EC measurements for top- and subsoil on each measurement site. Appendix Table 5 ([2]) depicts transformed EC results used in PCA and OLS regressions.

Table 14: Results of topsoil and subsoil pH on each measurement site.

Site	pH – results					
	Martenhoflacke		Moschadolacke		Illmitzer Zicksee	
	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil
1	8.72	8.59	8.28	8.31	8.71	9.03
2	8.63	8.53	8.21	8.40	8.57	9.09
3	8.66	8.72	8.14	8.49	8.79	9.01
4	7.98		8.14	8.49	8.95	9.18
5	7.63		8.07	8.44	8.48	8.33

Table 15: Results of topsoil and subsoil EC (2:3) in $\mu\text{S}/\text{cm}$ on each measurement site.

Site	EC (2:3) – results [$\mu\text{S}/\text{cm}$]					
	Martenhoflacke		Moschadolacke		Illmitzer Zicksee	
	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil
1	700	919	472	525	1411	2078
2	739	764	826	435	1010	2353
3	701	1026	451	436	1201	2291
4	404		682	338	2180	3129
5	748		460	385	1032	867

3.2.2. Soil cation content

The highest absolute soluble Na^+ was measured in the subsoil of Illmitzer Zicksee, particularly at site Zi4, while absolute soluble Na^+ at recently flooded or flooded saline soil sites Zi1 – Zi3 were comparable to non-flooded saline soils at Ma1 – Ma3. Absolute soluble K^+ was relatively low across sites although increased at sites with saline soil in Illmitzer Zicksee (Zi1 – Zi4). Mg^{2+} contents were overall lowest in saline soil sites at Martenhoflacke and slightly increased in Moschadolacke and some sites at Illmitzer Zicksee. Absolute soluble Ca^{2+} was increased particularly in the topsoil on P_{cov} sites as opposed to P_{uncov} sites which showed similarly low values across soda pans (Table 16). From a relative perspective, soluble cations were dominated by Na^+ in both Martenhoflacke and Illmitzer Zicksee across all sites with only slightly decreased relative contents at recently flooded or flooded sites Zi1 – Zi3. Moschadolacke in the topsoil was dominated by both soluble Ca^{2+} and Mg^{2+} as opposed to a relative dominance of soluble Na^+ in the subsoil. Results of absolute and relative soluble cations are shown in Table 16 – Table 17 and Figure 22. Appendix Table 6 shows results of transformed variables ([18] – [25]) as used in PCA and OLS regressions.

Exchangeable cations were dominated by the sum of bivalent cations Ca^{2+} and Mg^{2+} . Usually, exchangeable Mg^{2+} was lower (30 – 40 meq-%) than exchangeable Ca^{2+} (>45 meq-%), particularly in the subsoil. While Martenhoflacke was clearly dominated by Ca^{2+} , both Moschadolacke and Illmitzer Zicksee showed high Mg^{2+} levels across most sites as well. The percentage of exchangeable Na^+ ($\text{ESP}/\text{Na}(\text{meq}\%)$) was as high as >15 meq-% in P_{uncov} sites Ma1 – Ma3 and Zi4 as well as P_{cov} site Zi5. In Moschadolacke overall, exchangeable Na^+ was lower albeit still relatively high between 5 – 10 meq-%. In water-saturated or recently water-saturated sites (Zi3) at Illmitzer Zicksee exchangeable Na^+ reached only ≈ 10 meq-% in the topsoil which was lower than expected for drier topsoils in this lake. Furthermore, these sites were the only saline soil sites with lower Na^+ contents in the topsoil than in the subsoil. Exchangeable K^+ usually lay below 5 meq-%, however, slightly increased values were measured in the topsoil of Moschadolacke. Results of absolute and relative exchangeable cations are shown in Table 18 – Table 20 and Figure 23. Appendix Table 5 and Appendix Table 6 show results of transformed variables ([7] – [15]) as used in PCA and OLS regressions.

Table 16: Results of topsoil and subsoil absolute soluble cation content on each measurement site (variables: Na(H₂O), K(H₂O), Mg(H₂O), Ca(H₂O)).

Site	Soluble cations – results [mmol/kg fine soil]								
	Na ⁺		K ⁺		Mg ²⁺		Ca ²⁺		
	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil	
Martenhoflacke	1	62.6	39.1	4.3	4.5	< 3.1	< 3.1	3.7	3.0
	2	60.0	41.8	4.2	3.3	< 3.1	< 3.1	2.6	7.3
	3	47.0	47.0	3.6	3.6	< 3.1	< 3.1	4.9	4.9
	4	67.9		3.0		5.4		16.9	
	5	65.2		2.3		4.4		22.8	
Moschadolacke	1	20.6	18.5	5.4	2.9	6.7	7.7	9.4	12.1
	2	13.8	11.5	3.9	2.8	7.9	4.9	13.4	9.9
	3	6.0	16.7	3.7	3.2	9.6	6.9	10.7	9.2
	4	7.8	6.5	4.0	3.1	12.8	7.7	16.1	12.6
	5	5.5	15.4	3.4	4.3	10.4	6.2	14.3	9.0
Illmitzer Zicksee	1	54.8	78.3	8.6	6.9	8.4	3.0	4.4	4.9
	2	31.8	99.2	6.8	4.6	7.9	< 3.1	5.6	1.3
	3	54.8	94.0	6.8	6.1	12.3	4.4	6.3	1.8
	4	104.4	130.5	6.1	4.9	6.4	< 3.1	4.5	2.6
	5	47.0	33.9	3.4	3.8	5.2	5.9	3.4	8.1

Table 17: Results of topsoil and subsoil relative soluble cation content on each measurement site (variables: Na(H₂O%), K(H₂O%), Mg(H₂O%), Ca(H₂O%)).

Site	Soluble cations – results [mol-%]								
	Topsoil				Subsoil				
	Na ⁺	K ⁺	Mg ²⁺	Ca ²⁺	Na ⁺	K ⁺	Mg ²⁺	Ca ²⁺	
Martenhoflacke	1	85.1	5.8	4.2	5.0	78.8	9.0	6.2	6.0
	2	85.8	6.0	4.4	3.8	75.4	5.9	5.6	13.2
	3	80.2	6.1	5.3	8.4	80.2	6.2	5.3	8.4
	4	72.8	3.3	5.8	18.1				
	5	68.8	2.5	4.7	24.0				
Moschadolacke	1	49.0	12.8	15.8	22.4	45.0	7.1	18.6	29.4
	2	35.5	9.9	20.3	34.3	39.6	9.5	17.0	33.9
	3	20.0	12.3	32.0	35.7	46.3	8.9	19.2	25.5
	4	19.2	9.8	31.5	39.5	21.8	10.5	25.6	42.1
	5	16.3	10.1	30.9	42.7	44.2	12.3	17.7	25.8
Illmitzer Zicksee	1	71.9	11.3	11.0	5.8	84.1	7.4	3.2	5.2
	2	61.1	13.0	15.2	10.8	91.7	4.3	2.9	1.2
	3	68.4	8.4	15.4	7.8	88.3	5.8	4.2	1.7
	4	85.9	5.1	5.3	3.7	92.5	3.5	2.2	1.8
	5	79.7	5.8	8.8	5.7	65.5	7.4	11.4	15.7

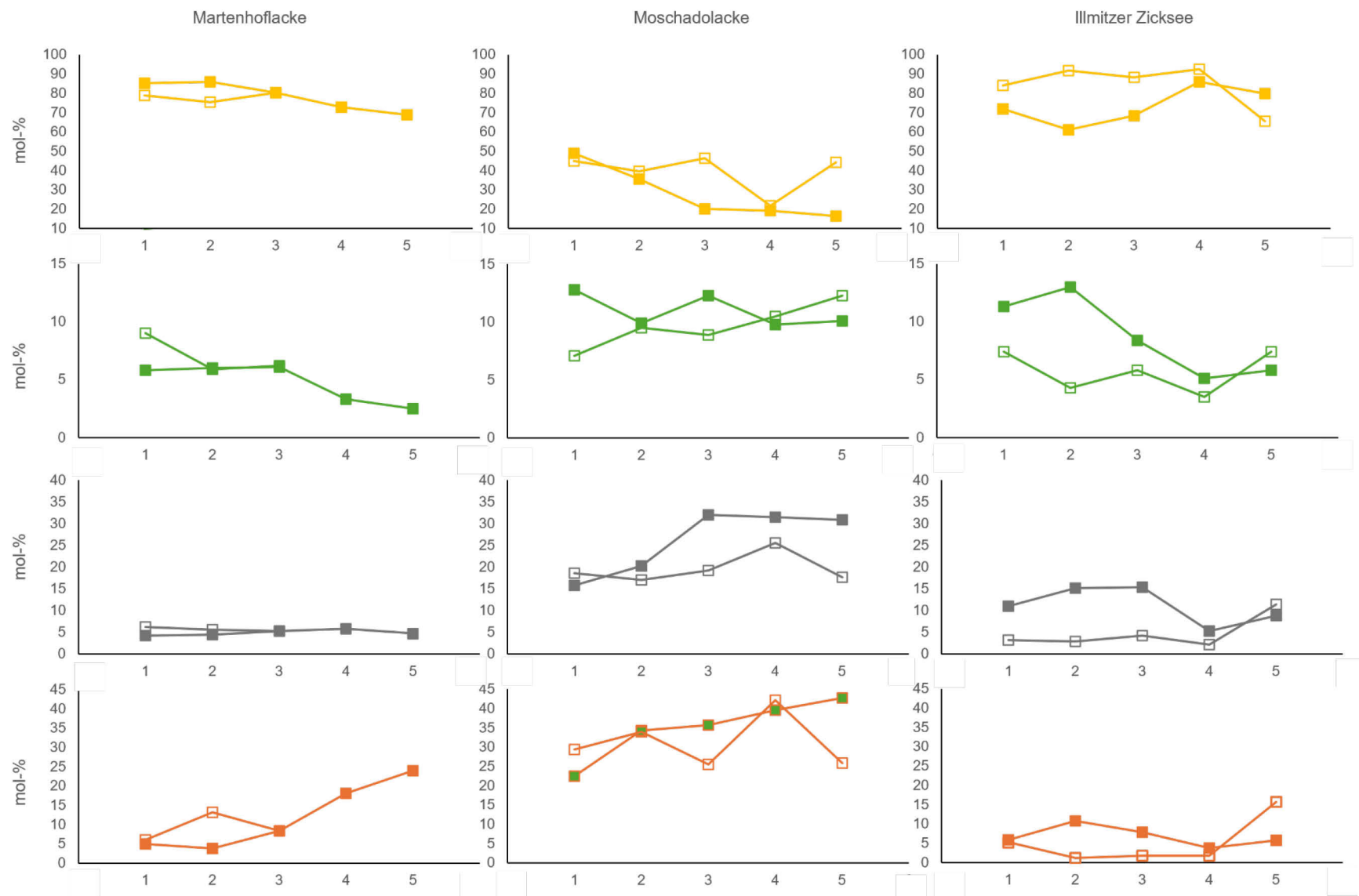


Figure 22: Results of relative topsoil and subsoil soluble cation content on each measurement site (yellow: Na(H₂O%), green: K(H₂O%), grey: Mg(H₂O%), orange: Ca(H₂O%); filled symbols: topsoil, empty symbols: subsoil).

Table 18: Results of topsoil and subsoil relative exchangeable cation content in mol-% on each measurement site (variables: Na(mol%), K(mol%), Mg(mol%), Ca(mol%)).

Site	Exchangeable cations – results [mol-%]								
	Topsoil				Subsoil				
	Na ⁺	K ⁺	Mg2+	Ca2+	Na ⁺	K ⁺	Mg2+	Ca2+	
Martenhoflacke	1	33.7	5.1	11.5	49.8	20.8	4.4	8.4	66.3
	2	29.1	5.3	12.8	52.8	20.8	3.9	13.0	62.3
	3	26.0	4.1	12.8	57.1	22.0	4.3	12.7	61.0
	4	12.4	9.8	24.1	53.8				
	5	6.6	5.8	14.3	73.3				
Moschadlacke	1	13.9	6.7	27.8	51.6	10.9	3.5	26.4	59.2
	2	23.7	11.3	28.3	36.7	9.1	4.4	23.4	63.1
	3	9.9	13.8	35.7	40.6	10.7	3.3	27	59.1
	4	8.9	10.2	36.4	44.5	4.7	3.3	27.1	64.9
	5	8.6	10.3	31.9	49.2	13.4	5.7	26.3	54.6
Illmitzer Zicksee	1	18.3	5.8	32.5	43.4	25.8	3.5	23.2	47.5
	2	17.8	5.3	30.8	46.2	25.9	3.0	20.9	50.2
	3	19.7	4.2	38.3	37.8	24.4	3.2	29.4	42.9
	4	39.0	4.5	19.5	37.0	33.7	2.9	18.7	44.7
	5	32.5	5.2	26.1	36.2	20.4	3.0	23.2	53.4

Table 19: Results of topsoil and subsoil relative exchangeable cation content in meq% on each measurement site (variables: Na(meq%), K(meq%), Mg(meq%), Ca(meq%)).

Site	Exchangeable cations – results [meq-%]								
	Topsoil				Subsoil				
	Na ⁺	K ⁺	Mg ²⁺	Ca ²⁺	Na ⁺	K ⁺	Mg ²⁺	Ca ²⁺	
Martenhoflacke	1	20.9	3.1	14.2	61.7	11.9	2.5	9.7	75.9
	2	17.6	3.2	15.5	63.7	11.9	2.2	14.8	71.1
	3	15.3	2.4	15.1	67.2	12.7	2.5	14.6	70.2
	4	6.9	5.5	27.1	60.5				
	5	3.5	3.1	15.2	78.2				
Moschadlacke	1	7.7	3.8	31	57.5	5.9	1.9	28.5	63.8
	2	14.4	6.9	34.3	44.4	4.9	2.3	25.1	67.7
	3	5.6	7.8	40.5	46	5.8	1.7	29.0	63.5
	4	4.9	5.7	40.2	49.2	2.5	1.7	28.2	67.6
	5	4.8	5.7	35.2	54.3	7.4	3.1	29.1	60.4
Illmitzer Zicksee	1	10.4	3.3	36.9	49.4	15.1	2.0	27.2	55.7
	2	10.0	3.0	34.8	52.2	15.2	1.7	24.4	58.7
	3	11.2	2.4	43.5	42.9	14.2	1.9	34.2	49.8
	4	24.9	2.9	25.0	47.2	20.6	1.8	22.9	54.7
	5	20.0	3.2	32.2	44.6	11.6	1.7	26.2	60.5

Table 20: Results of topsoil and subsoil relative exchangeable cation content in mmol and meq on each measurement site (variables: Na(molc), K(molc), Mg(molc), Ca(molc)).

Site		Exchangeable cations – results [mmol/kg = meq/kg fine soil]				Exchangeable cations – results [mmol/kg fine soil]				Exchangeable cations – results [meq/kg fine soil]			
		Na ⁺		K ⁺		Mg ²⁺		Ca ²⁺		Mg ²⁺		Ca ²⁺	
		Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil
Martenhoflacke	1	83.5	16.4	12.6	3.5	28.4	6.7	123.4	52.4	56.8	13.3	246.7	104.8
	2	60.0	14.6	10.9	2.7	26.4	9.1	108.7	43.7	52.8	18.3	217.4	87.4
	3	52.2	12.0	8.1	2.3	25.7	6.9	114.4	33.2	51.3	13.8	228.8	66.5
	4	8.4		6.6		16.3		36.4		32.6		72.8	
	5	5.2		4.6		11.4		58.2		22.7		116.5	
Moschadolacke	1	27.1	21.4	13.2	6.9	54.3	51.8	100.9	116.2	108.6	103.7	201.8	232.3
	2	13.8	17.2	6.6	8.3	16.5	44.4	21.4	119.6	33.1	88.9	42.8	239.2
	3	7.0	16.7	9.8	5.1	25.4	42	28.9	91.9	50.9	83.9	57.8	183.8
	4	7.6	8.6	8.7	6.0	31.1	49.4	38	118.3	62.2	98.7	76.1	236.5
	5	8.1	3.3	9.7	1.4	29.9	6.4	46.1	13.3	59.7	12.8	92.2	26.6
Illmitzer Zicksee	1	10.2	104.4	3.2	14.1	18	93.8	24.1	192.1	36.0	187.6	48.2	384.2
	2	13.8	102.1	4.1	12.0	23.9	83.9	35.9	202.1	47.9	167.9	71.9	404.2
	3	51.8	109.5	11.2	13.8	101.2	125.9	99.9	183.5	202.4	251.8	199.7	367.1
	4	88.7	151.4	10.3	13.2	44.4	83.9	84.1	201.1	88.9	167.9	168.3	402.1
	5	54.0	39.1	8.4	5.8	42	44.4	58.2	102.4	83.9	88.9	116.5	204.8

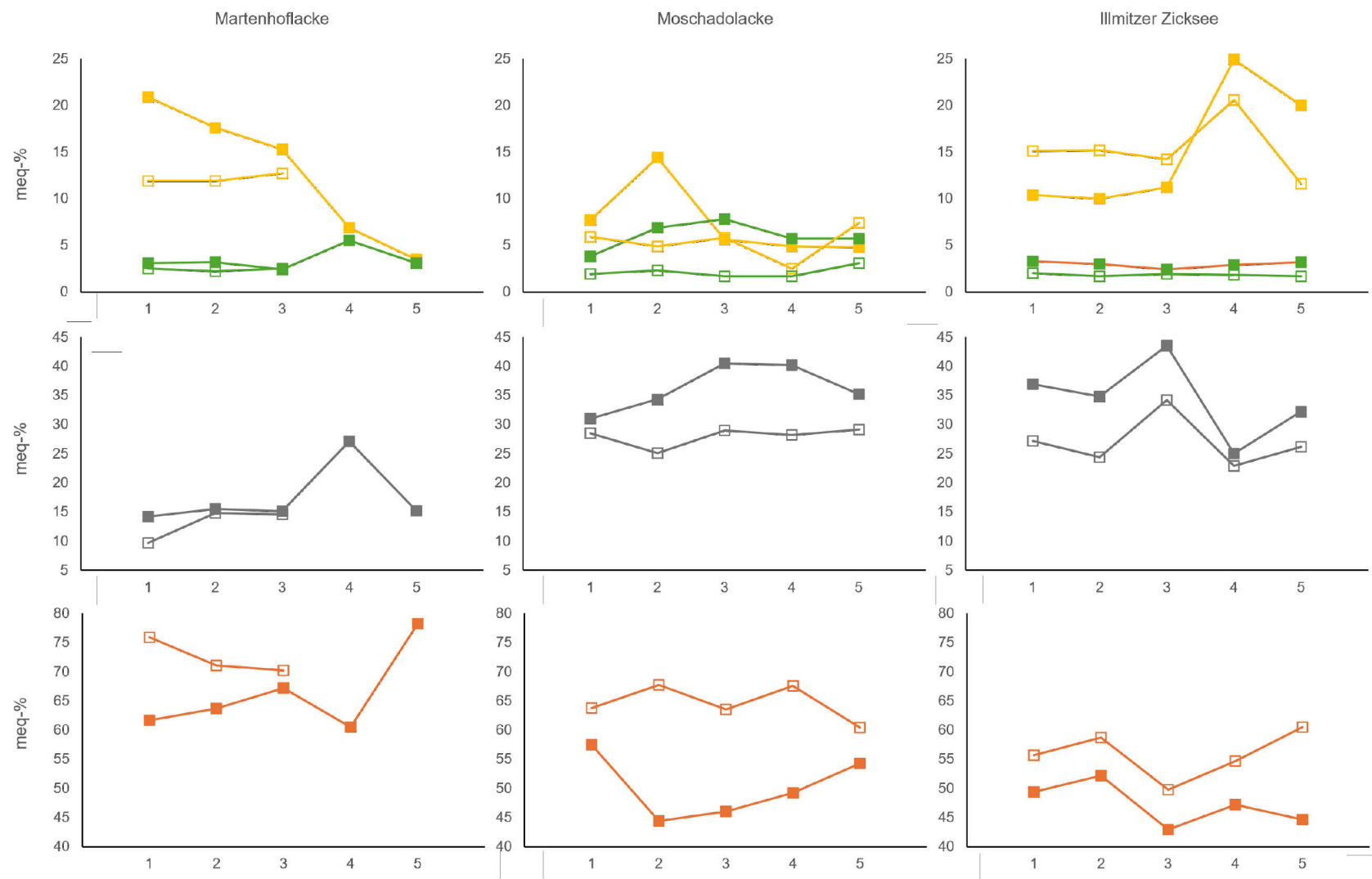


Figure 23: Results of topsoil and subsoil relative exchangeable cation content in meq-% on each measurement site (yellow: Na(meq%), green: K(meq%), grey: Mg(meq%), orange: Ca(meq%); filled symbols: topsoil, empty symbols: subsoil).

3.2.3. Soil cation content – derived values

3.2.3.1. Derived effective cation exchange capacities $CEC_{eff, AT}$ and $CEC_{eff, INT}$

CEC_{eff} , as the sum of cations, both for the Austrian and international calculation methods, showed similar patterns across soda pans. For Martenhoflacke, a high CEC_{eff} in the topsoil could be detected towards the center of the saline lake on P_{uncov} measurement points Ma1 – Ma3. A decline towards the subsoil similar to the topsoil at P_{cov} sites Ma4 and Ma5 was observed. Like Martenhoflacke, Moschadolacke showed high CEC_{eff} at P_{uncov} Mo1 and a sharp decline towards P_{cov} sites Mo2 – Mo5 in the topsoil. Subsoil CEC_{eff} was comparable (Mo1), much higher (Mo2 – Mo4), or lower (Mo5) than topsoil CEC_{eff} . At Illmitzer Zicksee, the highest CEC_{eff} was measured in the subsoil, reaching the highest overall values across soda pans. Topsoil CEC_{eff} on central, water-saturated areas was lowest and increased towards the edge reaching similar values than measured in central Martenhoflacke. Results of $CEC_{eff, AT}$ and $CEC_{eff, INT}$ are shown in Table 21 and Table 22. Appendix Table 5 shows results of transformed variables ([6], [11]) as used in PCA and OLS regressions.

Table 21: Results of topsoil and subsoil $CEC_{eff, AT}$ in mmol/kg fine soil on each measurement site.

Site	$CEC_{eff, AT}$ – results [mmol/kg fine soil]					
	Martenhoflacke		Moschadolacke		Illmitzer Zicksee	
	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil
1	247.8	79.0	195.6	196.3	55.5	404.4
2	206	70.2	58.4	189.6	77.9	402.4
3	200.4	54.5	71.2	155.7	264.5	427.6
4	67.6		85.4	182.2	227.6	449.6
5	79.4		93.7	24.4	160.8	191.8

Table 22: Results of topsoil and subsoil $CEC_{eff, INT}$ in meq/kg fine soil on each measurement site.

Site	$CEC_{eff, INT}$ – results [meq/kg fine soil]					
	Martenhoflacke		Moschadolacke		Illmitzer Zicksee	
	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil
1	399.6	138.0	350.8	364.3	97.6	690.3
2	341.1	123.0	96.3	353.6	137.7	688.4
3	340.4	94.6	125.5	289.5	465.5	737.1
4	120.3		154.6	349.9	356.2	734.6
5	149		169.7	44.1	261	338.7

3.2.3.2. Derived indices SAR and CROSS

Highest SAR and CROSS both in the topsoil and in the subsoil were measured in Illmitzer Zicksee at Zi4, reaching values of SAR >0.5 and CROSS >0.6. In the subsoil at Illmitzer Zicksee, similar values were reached on all P_{uncov} sites (Zi1 – Zi4). Topsoil indices were strongly reduced on (recently) water-saturated sites (Zi1 – Zi3). At Martenhoflacke, both indices were lower in the topsoil than in Illmitzer Zicksee and gradually decreased from the center to the edge of the lake. In the subsoil, SAR and CROSS were similar and comparable to relatively low values measured in central areas at Moschadolacke, both in the topsoil and in the subsoil. In Moschadolacke, SAR and CROSS values were similar across the whole transect, with slight increases towards the center of the lake. Table 23 and Table 24 show the results of SAR and CROSS. Appendix Table 6 ([16], [17]) depicts transformed SAR and CROSS results used in PCA and OLS regressions.

Table 23: Results of topsoil and subsoil SAR on each measurement site.

Site	SAR – results					
	Martenhoflacke		Moschadolacke		Illmitzer Zicksee	
	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil
1	0.48	0.15	0.15	0.12	0.11	0.44
2	0.37	0.14	0.16	0.1	0.13	0.44
3	0.31	0.13	0.07	0.1	0.26	0.42
4	0.08		0.06	0.05	0.55	0.63
5	0.04		0.07	0.05	0.37	0.23

Table 24: Results of topsoil and subsoil CROSS on each measurement site.

Site	CROSS – results					
	Martenhoflacke		Moschadolacke		Illmitzer Zicksee	
	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil
1	0.54	0.17	0.21	0.15	0.14	0.5
2	0.42	0.16	0.22	0.13	0.16	0.49
3	0.35	0.15	0.13	0.13	0.33	0.49
4	0.13		0.12	0.07	0.63	0.71
5	0.07		0.12	0.07	0.44	0.26

3.2.3.3. Derived minimal salt content

Calculated minimal salt contents were highest on P_{uncov} sites in the subsoil of Illmitzer Zicksee (Zi1 – Zi4). The topsoil maximum was reached at Zi4 with 0.72 wt.%, (recently) water-saturated or P_{cov} sites showed lower values, although still >0.3 wt.%. At Martenhoflacke, $\text{salt}_{\text{min}}\%$ was similar across saline soil sites Ma1 – Ma3, both in the topsoil and in the subsoil. Highest salt contents were calculated for topsoil in the P_{cov} areas of Ma4/Ma5, and no site showed salt contents <0.3 wt.%. At Moschadolacke all sites lay below this threshold between 0.15 and 0.25 wt.% both in the topsoil and in the subsoil. Table 25 shows the results of the calculations for minimal salt content. Appendix Table 6 ([26]) depicts transformed $\text{salt}_{\text{min}}\%$ results used in PCA and OLS regressions.

Table 25: Results of topsoil and subsoil minimal salt content in wt.% on each measurement site.

Site	Theoretical minimal soluble salt content – results [wt.%]					
	Martenhoflacke		Moschadolacke		Illmitzer Zicksee	
	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil
1	0.44%	0.30%	0.25%	0.24%	0.45%	0.55%
2	0.41%	0.33%	0.23%	0.17%	0.31%	0.64%
3	0.35%	0.35%	0.18%	0.21%	0.47%	0.63%
4	0.55%		0.24%	0.18%	0.72%	0.83%
5	0.57%		0.20%	0.21%	0.35%	0.31%

3.2.4. Soil carbon content

In general, relative soil organic carbon (OC%) showed a tendency of lower values at P_{uncov} sites as opposed to P_{cov} sites. Highest OC% levels were reached in the topsoil on the edge of Martenhoflacke (2.25 wt.%), which was more than twice as high as the second highest OC% measured (Topsoil Mo5: 0.97 wt.%). In the topsoil P_{uncov} sites in Martenhoflacke, Ma1 – Ma3 showed the lowest measured OC% (≈ 0.25 wt.%). At Moschadolacke, the lowest organic carbon in the topsoil was also measured in the only P_{uncov} site at Mo1, reaching values almost as low as in Ma1. After a sharp increase towards Mo2, values stayed relatively high at Mo4 and Mo5 (≈ 1 wt.%) after a slight decrease at Mo3. Subsoil OC% levels in both soda pans were comparable at approximately 0.1 wt.%. At Illmitzer Zicksee, on saline soil sites Zi1 – Zi4, topsoil OC% was higher than on similar sites at Martenhoflacke, although a similar increase towards the edge of the lake and P_{cov} sites could be observed. Subsoil OC% was increased particularly in non- water-saturated areas Zi3 – Zi5. Table 26 shows the results of OC% measurements. Appendix Table 6 ([27]) depicts transformed OC% results used in PCA and OLS regressions.

Relative soil inorganic carbon/carbonate content was high across all measurement sites. However, levels in the topsoil of Martenhoflacke were considerably lower than in the subsoil and on all other measurement sites (< 2 wt.%). Subsoil values on saline soil sites, however, were comparable to other subsoil values. In Moschadolacke, the highest IC% was measured in the topsoil and the subsoil at P_{uncov} Mo1. Similar values of ≈ 2.5 wt.% in the topsoil and ≈ 3 wt.% in the subsoil (exception Mo5) were observed on P_{cov} sites in this lake. At Illmitzer Zicksee, the highest IC% contents were detected reaching up to ≈ 5 wt.% in the topsoil of Zi1, Zi4 and Zi5, as well as in the subsoil of Zi4. Other sites showed high values of > 3 wt.% as well, whereby higher values were usually observed in the topsoil, as opposed to the subsoil. Table 27 shows the results of IC% measurements and Table 28 depicts results of (theoretical) carbonate content calculations from IC%. Appendix Table 6 ([28]) shows transformed IC% results used in PCA and OLS regressions.

Table 26: Results of topsoil and subsoil organic carbon content in wt.% on each measurement site. P_{cov} sites are marked green.

Site	Organic carbon content – results [wt.%]					
	Martenhoflacke		Moschadolacke		Illmitzer Zicksee	
	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil
1	0.23%	0.10%	0.29%	0.09%	0.47%	0.14%
2	0.22%	0.10%	0.89%	0.14%	0.35%	0.08%
3	0.22%	0.07%	0.60%	0.11%	0.37%	0.21%
4	0.78%		0.93%	0.07%	0.68%	0.28%
5	2.25%		0.97%	0.04%	0.91%	0.36%

Table 27: Results of topsoil and subsoil inorganic carbon content in wt.% on each measurement site.

Site	Inorganic carbon content – results [wt.%]					
	Martenhoflacke		Moschadolacke		Illmitzer Zicksee	
	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil
1	1.74%	2.98%	3.39%	4.21%	5.05%	3.56%
2	1.79%	4.81%	2.31%	3.09%	3.68%	3.19%
3	1.86%	3.19%	2.59%	3.09%	4.43%	4.03%
4	1.38%		2.71%	3.19%	5.00%	5.28%
5	1.32%		2.87%	1.65%	5.19%	4.59%

Table 28: Results of IC% derived topsoil and subsoil carbonate content in wt.% on each measurement site.

Site	Derived carbonate content – results [wt.%]					
	Martenhoflacke		Moschadolacke		Illmitzer Zicksee	
	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil
1	8.7%	14.9%	17.0%	21.0%	25.2%	17.8%
2	9.0%	24.1%	11.5%	15.4%	18.4%	15.9%
3	9.3%	15.9%	13.0%	15.4%	22.1%	20.1%
4	6.9%		13.6%	15.9%	25.0%	26.4%
5	6.6%		14.3%	8.3%	25.9%	22.9%

3.2.5. Topsoil bulk density and water content

Topsoil bulk density was highest at Ma3 and Ma4, reaching $\approx 1.7 \text{ g/cm}^3$. The plateau at Ma3 and Ma4 (P_{uncov} and P_{cov} respectively) was reached after a slight increase from the central point Ma1 $\approx 1.55 \text{ g/cm}^3$. After the plateau, BD dropped strongly towards Ma5 reaching values of only $\approx 1.4 - 1.45 \text{ g/cm}^3$. At Moschadolacke BD was highest at Mo1 with $\approx 1.65 \text{ g/cm}^3$, followed by a sharp decrease to the lowest value of $\approx 1.25 \text{ g/cm}^3$ at Mo2. From Mo3 to Mo5, BD values stayed at $\approx 1.35 \text{ g/cm}^3$ with a slight decrease towards the edge of the lake. Measured values at Illmitzer Zicksee Zi3 – Zi5 showed a gradual decrease from Zi3 (BD $\approx 1.5 \text{ g/cm}^3$) towards the edge at Zi5 (BD $\approx 1.35 \text{ g/cm}^3$). Table 29 depicts the results of topsoil BD measurements.

Topsoil water content decreased from central areas towards the edge of both Martenhoflacke and Illmitzer Zicksee, apart from a slight increase between P_{uncov} Ma3 and P_{cov} Ma4. The lowest overall WC was measured in Ma5 (P_{cov}), reaching only 3 wt.% which was more than twice as low as second lowest site Ma3 (8 wt.%). From their WC both central areas of Martenhoflacke and unsaturated saline soil sites at Illmitzer Zicksee Zi3 – Zi5 were comparable. At Moschadolacke WC levels were lower than on saline soil sites and remained similar regardless of P_{cov} status with the exception of reed covered Mo2 which reached the maximum WC of all soda pans only comparable to Ma1. Table 30 shows the results of topsoil WC measurements.

Table 29: Results of topsoil bulk density in g/cm^3 on each measurement site.

Site	Bulk density – results [g/cm^3]		
	Martenhoflacke	Moschadolacke	Illmitzer Zicksee
1	1.57	1.67	
2	1.62	1.25	
3	1.68	1.46	1.49
4	1.68	1.44	1.46
5	1.43	1.42	1.34

Table 30: Results of topsoil water content in wt.% on each measurement site.

Site	Water content – results [wt.%]		
	Martenhoflacke	Moschadolacke	Illmitzer Zicksee
1	22	11	
2	18	22	
3	8	11	19
4	11	14	18
5	3	15	16

3.2.6. Soil texture

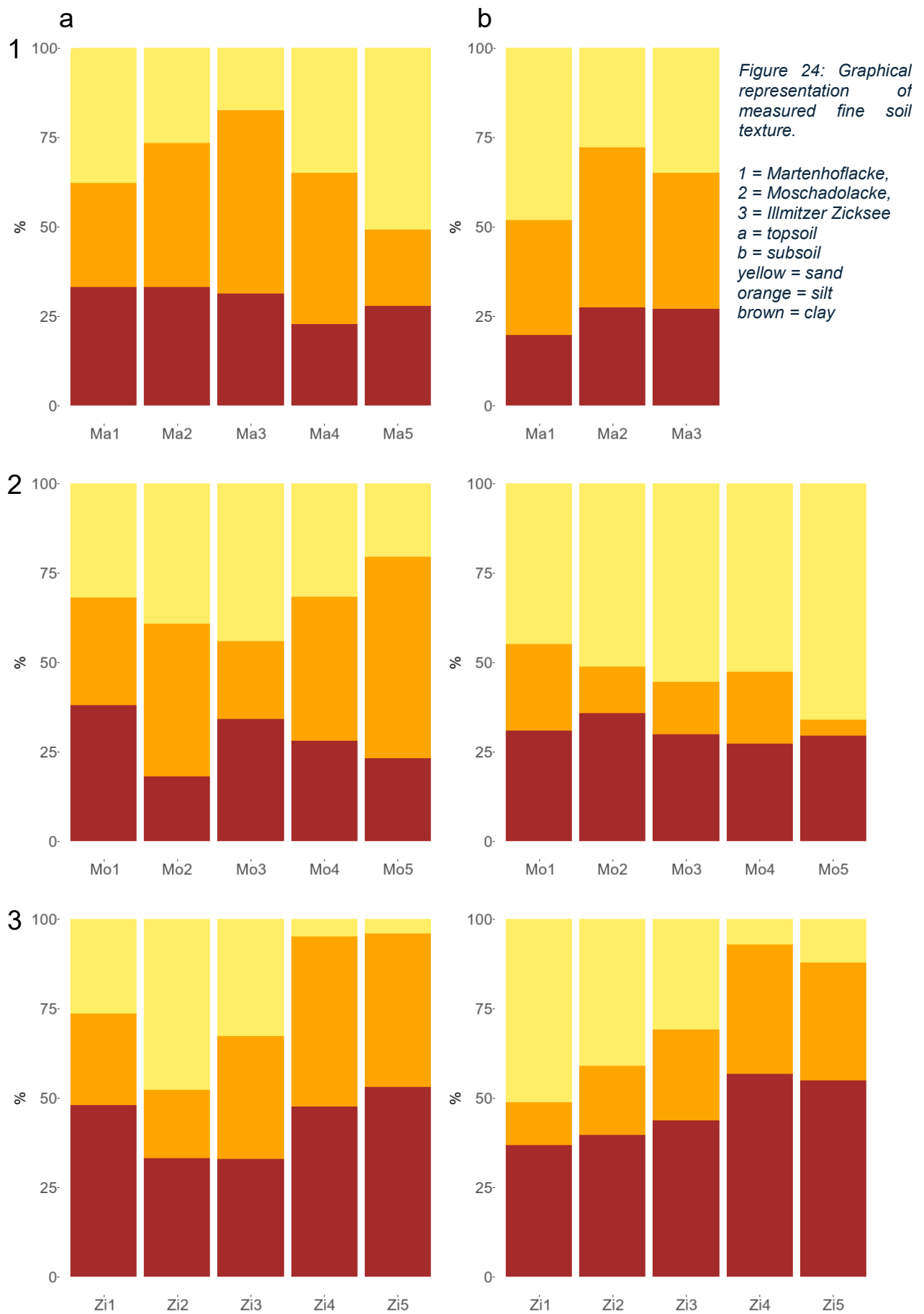
Estimating the coarse fraction resulted in sites dominated by fine soil, apart from the edge areas of Martenhoflacke and the central areas of Moschadolacke and Illmitzer Zicksee. According to the Austrian texture classification, conditions at Martenhoflacke were mostly described by loam. This held true for other soda pans as well. However, Illmitzer Zicksee exhibited overall increased clay levels particularly on sites close to the edge of the lake. Following the WRB international classification, conditions at Martenhoflacke are mostly described as clay loam, while Moschadolacke shows a clay loam texture mixed with silt at Mo5 in the topsoil and clay/loam conditions in the subsoil. Illmitzer Zicksee showed various texture conditions mostly dominated by clay and loam, mixed with sand towards the center of the lake and silt at the edge of the lake. The highest overall topsoil clay content was reached at Zi5 (53 wt.%) and at Zi4 in the subsoil (>55 wt.%). The lowest clay contents were found in the topsoil of Mo2 (≈ 18 wt.%), while subsoil clay contents did not fall below 27% (Mo2). Sand contents reached their minimum in the topsoil at Zi4 and Zi5 (<5 wt.%) and increased up to 66 wt.% in the subsoil at Mo5. Table 31 gives an overview of Austrian and International fine soil texture classification for each site, Table 32 shows all measurement results and Figure 24 gives a graphical representation of fine soil texture in each soda pan. For logit transformed sand%, silt% and clay% variables refer to Appendix Table 5 ([3] – [5]).

Table 31: Soil texture classification of measurement sites for Austrian and International classifications.

Site	Soil texture classification – Austrian classification					
	Martenhoflacke		Moschadolacke		Illmitzer Zicksee	
	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil
1	loam	sandy loam	loam	loam	loamy clay	loam
2	loam	loam	sandy loam	loam	loam	loam
3	loam	loam	loam	loam	loam	loamy clay
4	sandy loam		loam	loam	loamy clay	clay
5	loam		loamy silt	sandy clay	clay	clay
Site	Soil texture classification – International classification					
	Martenhoflacke		Moschadolacke		Illmitzer Zicksee	
	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil
1	clay loam	loam	clay loam	clay loam	clay	sandy clay loam
2	clay loam	clay loam	loam	sandy clay	sandy clay loam	clay loam
3	silty clay loam	clay loam	clay loam	sandy clay loam	clay loam	clay loam
4	clay loam		clay loam	sandy clay loam	silty clay	clay
5	sandy clay loam		silt loam	sandy clay loam	silty clay	clay

Table 32: Results of topsoil and subsoil soil texture on each measurement site.

Martenhoflacke	Coarse fraction [wt.% raw soil]		Fine soil texture [wt.% fine soil]					
	> 2 mm (>2mm%)		2 – 0.063 mm (sand%)		0.063 – 0.002 mm (silt%)		<0.002 mm (clay%)	
Site	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil
1	1%	6%	37.8%	48.2%	29.1%	32.1%	33.1%	19.7%
2	1%	<0.1%	26.6%	27.8%	40.2%	44.7%	33.2%	27.5%
3	8%	11%	17.5%	35.0%	51.2%	38.0%	31.3%	27.0%
4	16%		35.0%		42.2%		22.8%	
5	41%		50.9%		21.3%		27.8%	
Moschadolacke	> 2 mm (>2mm%)		2 – 0.063 mm (sand%)		0.063 – 0.002 mm (silt%)		<0.002 mm (clay%)	
	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil
1	35%	25%	32.0%	45.0%	29.9%	24.0%	38.1%	31.0%
2	1%	6%	39.3%	51.2%	42.6%	13.0%	18.1%	35.8%
3	2%	11%	44.2%	55.6%	21.7%	14.5%	34.1%	29.9%
4	1%	8%	31.7%	52.6%	40.2%	20.1%	28.1%	27.3%
5	5%	22%	20.5%	66.0%	56.3%	4.5%	23.2%	29.5%
Illmitzer Zicksee	> 2 mm (>2mm%)		2 – 0.063 mm (sand%)		0.063 – 0.002 mm (silt%)		<0.002 mm (clay%)	
	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil
1	6%	26%	26.5%	51.2%	25.6%	12.0%	47.9%	36.8%
2	32%	5%	47.8%	41.0%	19.2%	19.3%	33.0%	39.7%
3	<0.1%	<0.1%	32.7%	31.0%	34.4%	25.4%	32.9%	43.6%
4	<0.1%	<0.1%	4.9%	7.2%	47.5%	36.0%	47.6%	56.8%
5	<0.1%	3%	4.2%	12.2%	42.8%	33.0%	53.0%	54.8%



3.2.7. Soil and clay mineralogy

An examination of bulk soil mineralogical composition for all soda pans revealed contents of quartz, albite, microcline, dolomite, calcite, muscovite and chlorite across all soda pans. Dolomite-peaks, particularly in the topsoil of Illmitzer Zicksee and lower soil of Moschadolacke showed broad peaks which indicate the presence of protodolomite. At Martenhoflacke dolomite peaks were well defined, indicating a dominance of dolomite rather than protodolomite. Furthermore, sodium-containing feldspar albite was clearly present within all soils, whereby no signs of significant albite weathering through absence of albite could be detected.

Further examination of clay mineralogy in the upper and lower soil at central measurement points Ma1, Mo1 and Zi1 revealed the dominance of illite and chlorite across all soda pans' clay fractions. Peaks of illite and chlorite were relatively well defined, indicating good crystallization. Furthermore, particularly in Moschadolacke and Illmitzer Zicksee protodolomite was a dominating factor with a maximum in the subsoil at Mo1 and similar contents for Mo1 topsoil and both top- and subsoil at Zi1. At Martenhoflacke tiny amounts of protodolomite and calcite were present in the clay fraction of the subsoil, while the topsoil at Ma1 did not contain significant amounts of carbonate minerals. Smectite was only found at Zi1, mainly in the lower soil. Appendix chapter 6.7 show XRD results both for bulk soil mineralogical composition as well as clay mineralogy at the examined measurement points.

3.2.8. Soil cracks

Limited observations on saline soils at Ma2 and Zi3 at the end of August 2024 shortly after the measurement of WC, reveal a tendency for shrinkage cracks in the order of Zi3 followed by Zi4 and Ma2. Figure 25 shows shrinkage cracks on all three measurement sites at 30.08.2024.

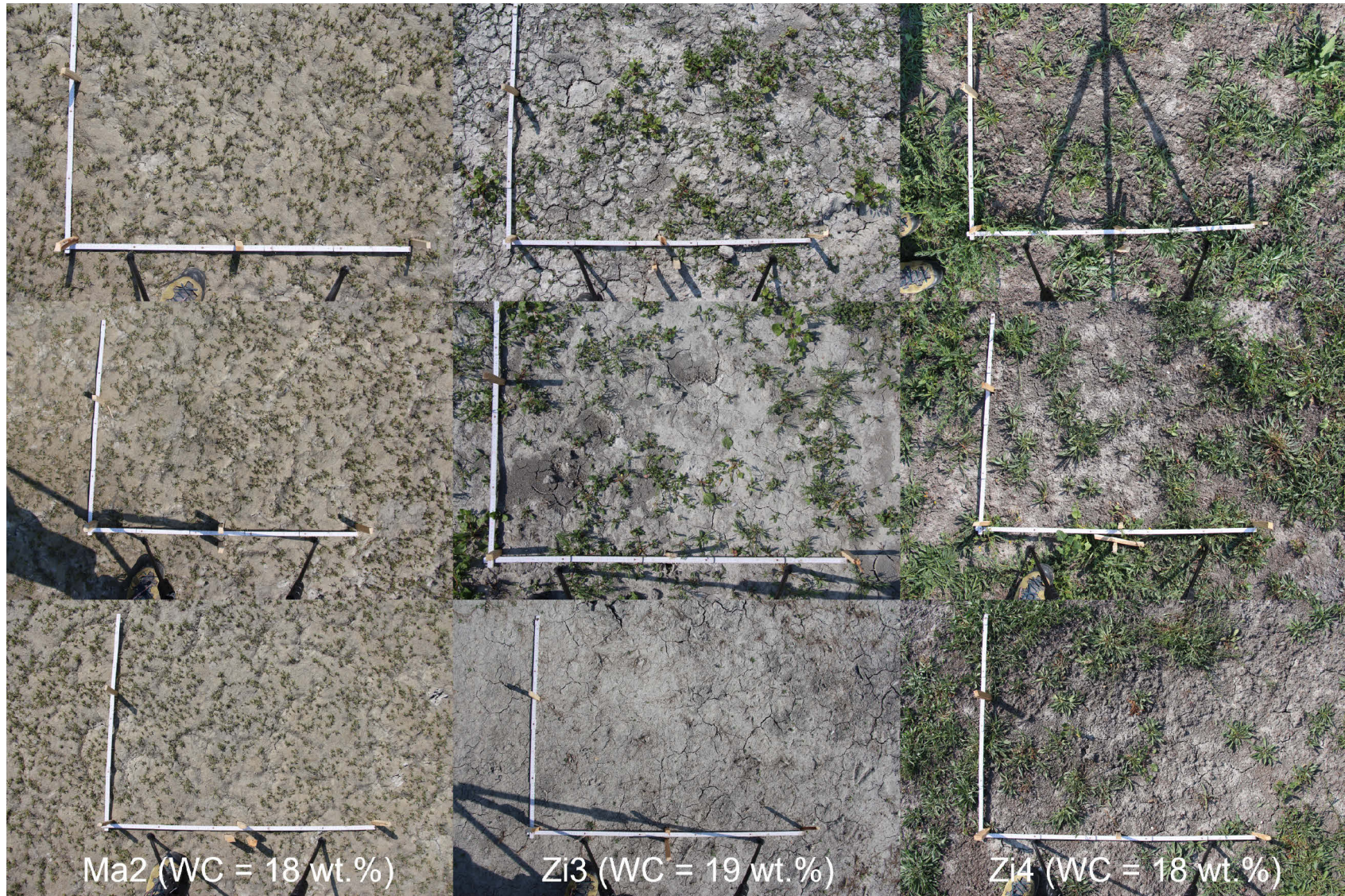


Figure 25: Soil cracks on measurement sites Ma2, Zi3 and Zi4 at WC of ≈ 18 wt. %.

3.3. Measurement evaluation: Soil properties

3.3.1. Classification: Saline soils on measurement sites

Comparing the necessary chemical soil attributes pH, EC_e (chapter 2.2.3), salt content ($salt_{min}\%$) and exchangeable Na^+ ($Na(mol\%)$) as well as Mg^{2+} ($Mg(mol\%)$) yielded results as shown in Table 33. As the zonation of Martenhoflacke suggests, a change of soil types is detectable between the central P_{uncov} (Ma1 – Ma3) and outer P_{cov} (Ma4 – Ma5) areas. The central areas fulfill at least 2/3 criteria to be classified as Solontschak-Solonetz (apart from EC_e) both for the topsoil and for the subsoil, as well as showing typical features such as little vegetation cover (Appendix 1 – Appendix 2) and low SHC. The outer areas however do not fulfill the criteria to be classified as one of the saline soil types according to the Austrian classification. In Illmitzer Zicksee, chemical parameters showed a relatively clear Solontschak-Solonetz soil type across measurement sites, which was supported by patchy vegetation mostly formed by halophytes (Appendix 4 – Appendix 5). Only Zi5 showed a closed plant cover meadow-like vegetation pattern (Appendix 6), however chemical parameters particularly in the topsoil still supported a classification as Solontschak-Solonetz soil. Lastly, measurement sites at Moschadolacke soils did not sufficiently fulfill criteria for classification as a saline soil, mainly because measured pH was too low for classification as a Solonetz soil in both the upper and in the subsoil. Solonetz status would have to be determined by analyzing soil profiles and soil structure, which was not the scope of this study. Consequently, measurement sites Ma1 – Ma3 and Zi1 – Zi5 could be classified as saline soil sites (Solontschak-Solonetz). Soils on the other measurement sites were either not clearly saline or of a different soil type.

Comparing SHC for different soil textures (Table 2) with soils found in soda pans shows that in central Martenhoflacke Ma1 – Ma3 soils had much lower SHC than could be expected for loamy soils. Clayey soils at Illmitzer Zicksee, however, showed SHC values that could be expected from this type of soil texture. At Moschadolacke only the loamy soil at Mo1 showed lower SHC than expected from literature values. The other measurements at Mo2 – Mo5 lay within the SHC range for loamy textures as defined in the literature.

Table 33: Relevant soil properties and saline soil classification on each measurement site

Measurement site		Saline soil classification										Saline soil type
		Topsoil					Subsoil					
		pH	EC _e	Salt min%	Na (mol%)	Mg (mol%)	pH	EC _e	Salt min%	Na (mol%)	Mg (mol%)	
Martenhoflacke	1	8.72	2386	0.44%	33.70%	11.45%	8.59	5514	0.30%	20.82%	8.44%	Solontschak-Solonetz
	2	8.63	2519	0.41%	29.14%	12.82%	8.53	2605	0.33%	20.82%	13.01%	Solontschak-Solonetz
	3	8.66	2390	0.35%	26.05%	12.81%	8.72	3498	0.35%	22.03%	12.69%	Solontschak-Solonetz
	4	7.98	1263	0.55%	12.35%	24.09%						Other soil type
	5	7.63	2244	0.57%	6.57%	14.30%						Other soil type
Moschadolacke	1	8.28	1539	0.25%	13.88%	27.77%	8.31	1790	0.24%	10.90%	26.41%	Other soil type
	2	8.21	4272	0.23%	23.69%	28.33%	8.4	1279	0.17%	9.09%	23.44%	Other soil type
	3	8.14	1409	0.18%	9.90%	35.72%	8.49	2044	0.21%	10.73%	26.96%	Other soil type
	4	8.14	2131	0.24%	8.86%	36.40%	8.49	1584	0.18%	4.73%	27.09%	Other soil type
	5	8.07	2156	0.20%	8.63%	31.87%	8.44	1805	0.21%	13.38%	26.32%	Other soil type
Illmitzer Zicksee	1	8.71	3256	0.45%	18.33%	32.46%	9.03	9738	0.55%	25.81%	23.20%	Solontschak-Solonetz
	2	8.57	4591	0.31%	17.77%	30.76%	9.09	8020	0.64%	25.94%	20.86%	Solontschak-Solonetz
	3	8.79	3916	0.47%	19.74%	38.27%	9.01	7811	0.63%	24.41%	29.44%	Solontschak-Solonetz
	4	8.95	4809	0.72%	38.99%	19.52%	9.18	7220	0.83%	33.67%	18.67%	Solontschak-Solonetz
	5	8.48	2276	0.35%	32.45%	26.09%	8.33	2001	0.31%	20.41%	23.17%	Solontschak-Solonetz

3.3.2. PCA: Topsoil properties

The PCA conducted for topsoil properties yielded 14 Principal Components (PC), however PC1_{up} – PC4_{up} already accounted for >85% of total variance (see Table 34). Consequently, PC1_{up} – PC4_{up} were further analyzed according to their influence on SHC. Tables 35 give an overview of OLS correlation strengths for singular topsoil properties and PC values, Appendix Table 9 shows factor loadings in the form of OLS correlations.

Table 34: Principal components for topsoil properties (PC_{up}).

PC _{up}	Eigenvalue	% variance
1	16.7	44.1
2	8.9	23.3
3	4.9	13.0
4	2.7	7.2

Tables 35: OLS correlation strengths of relevant principal components (topsoil PCA) and topsoil properties.

PC1 _{up}		
correlations	r > 0	r < 0
R ² > 0.55 p < 0.05	Na(meq) > SAR > CROSS > CEC _{eff, AT} = Na(mol%) > Na(meq%) > CEC _{eff, INT} > pH > Na(H ₂ O%) > Ca(meq)	Ca(H ₂ O) > Ca(H ₂ O%) > K(mol%) > K(meq%)
0.35 < R ² < 0.55 p < 0.05	Na(H ₂ O) > salt _{min} % > clay%	Mg(H ₂ O%) > OC%
R ² < 0.35 p < 0.05		Mg(H ₂ O) > Mg(meq%)
R ² < 0.35 0.05 < p < 0.1	EC	sand%
PC2 _{up}		
correlations	r > 0	r < 0
R ² > 0.55 p < 0.05	Mg(meq%) > Mg(mol%) > IC% > K(H ₂ O%) > Mg(H ₂ O)	Ca(meq%) > Ca(mol%)
0.35 < R ² < 0.55 p < 0.05	Mg(molc)	
R ² < 0.35 p < 0.05		>2mm%
R ² < 0.35 0.05 < p < 0.1		Na(H ₂ O)
R ² > 0.55 p > 0.1	K(H ₂ O%)	
PC3 _{up}		
correlations	r > 0	r < 0
R ² > 0.55 p < 0.05	K(meq)	
0.35 < R ² < 0.55 p < 0.05	EC	
R ² < 0.35 p < 0.05	Na(H ₂ O)	
R ² < 0.35 0.05 < p < 0.1	salt _{min} %	
PC4 _{up}		
correlations	r > 0	r < 0
R ² < 0.35 p < 0.05		silt%
0.35 < R ² < 0.55 0.05 < p < 0.1	>2mm%	
R ² < 0.35 0.05 < p < 0.1		Na(mol%)

The following Figure 27 shows a biplot of $PC1_{up}$ and $PC2_{up}$ (67.4% variance) and plant-covered as well as water-saturated sites. All sites at Martenhoflacke showed negative $PC2_{up}$ values and followed the general trend of negative $PC1_{up}$ values for P_{cov} and positive values for sites with P_{uncov} status. At Moschadolacke, all sites exhibited positive $PC2_{up}$ values and followed the trend for P_{cov} as described above. Sites at Illmitzer Zicksee were split between water-saturated and unsaturated sites, while P_{cov} status did not result in negative $PC1_{up}$ values. All $PC2_{up}$ values at Illmitzer Zicksee were positive. Figure 26 depicts results of $PC1_{up} - PC4_{up}$ at all sites, Appendix Table 7 shows exact numerical results of $PC1_{up} - PC4_{up}$.

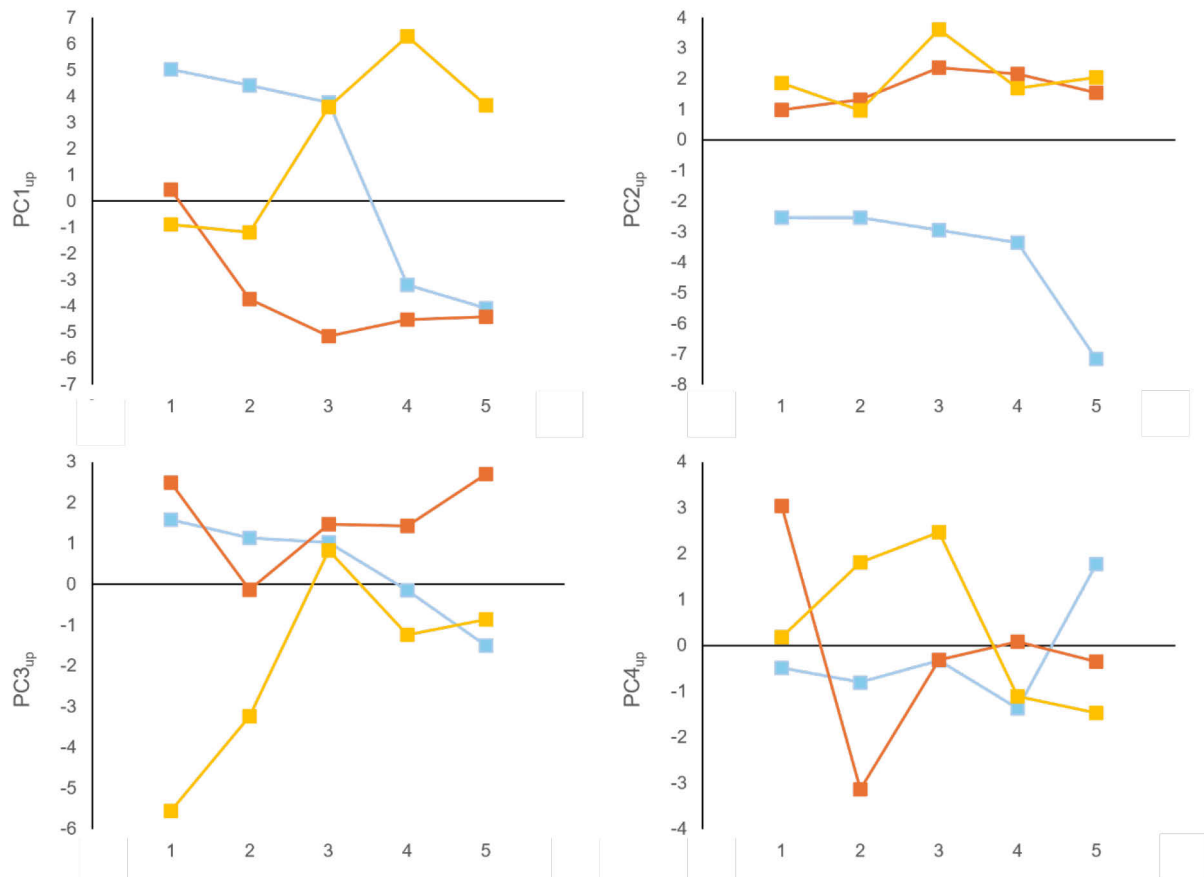


Figure 26: Results of $PC1_{up} - PC4_{up}$ (blue = Martenhoflacke, red = Moschadolacke, orange = Illmitzer Zicksee).

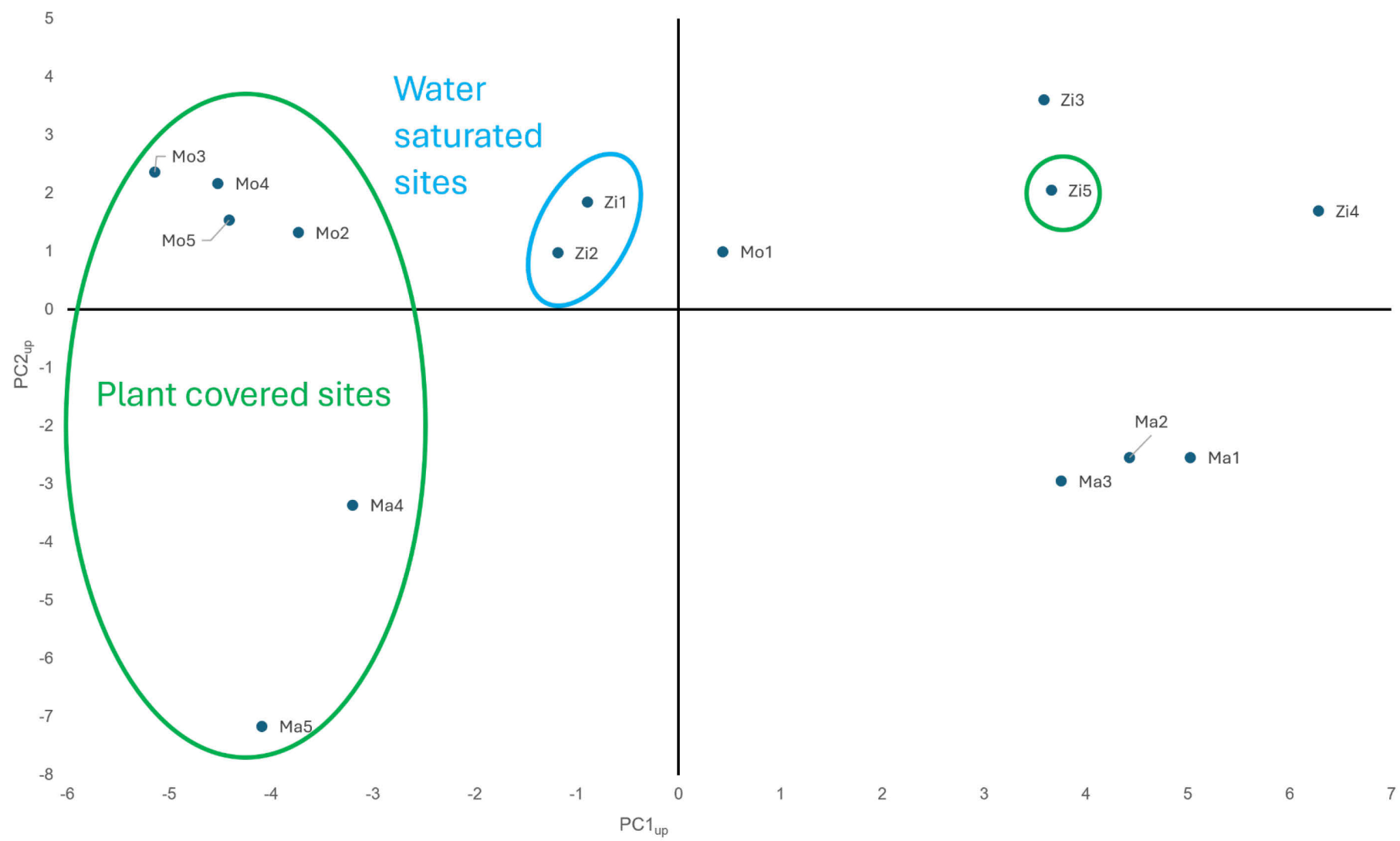


Figure 27: Biplot of PC1_{up} and PC2_{up}.

3.3.3. PCA: Subsoil properties

The PCA conducted for subsoil properties yielded 12 PC, however PC1_{low} – PC3_{low} already accounted for >85% of total variance (Table 37). Consequently, PC1_{low} – PC3_{low} were further analyzed according to their influence on SHC. Tables 36 give an overview of OLS correlation strengths for singular subsoil properties and PC values, Appendix Table 10 shows factor loadings in the form of OLS correlations.

Table 37: Principal Components for subsoil properties (PC_{low}).

PC _{low}	Eigenvalue	% variance
1	21.4	56.2
2	8.3	21.8
3	4.0	10.6

Tables 36: OLS correlation strengths of relevant principal components (subsoil PCA) and subsoil properties

PC1 _{low} correlations	r > 0	r < 0
R ² > 0.55 p < 0.05	Na(meq) > CROSS > SAR > EC > salt _{min} % > Na(H ₂ O) > CEC _{eff, AT} > Na(H ₂ O%) > K(meq) > CEC _{eff, INT} > pH > Ca(meq)	K(H ₂ O%) > Ca(H ₂ O%) > Mg(H ₂ O%) > Ca(mol%) > K(mol%)
0.35 < R ² < 0.55 p < 0.05	Na(mol%) > Na(meq%) > clay% > OC% > Mg(meq) > IC% > K(H ₂ O)	Ca(H ₂ O) > sand% > Ca(meq%)
R ² < 0.35 p < 0.05		Mg(H ₂ O)
R ² < 0.35 0.05 < p < 0.1		>2mm%

PC2 _{low} correlations	r > 0	r < 0
R ² > 0.55 p < 0.05	Mg(mol%) > Mg(meq%) > Mg(H ₂ O)	
0.35 < R ² < 0.55 p < 0.05		Na(meq%) > K(meq%) > Na(mol%)
R ² < 0.35 p < 0.05	Mg(H ₂ O%) > Ca(H ₂ O)	
R ² < 0.35 0.05 < p < 0.1	Ca(H ₂ O%)	Na(H ₂ O%) > salt _{min} %
0.35 < R ² < 0.55 p > 0.1	Mg(molc)	

PC3 _{low} correlations	r > 0	r < 0
R ² > 0.55 p < 0.05		silt%
R ² < 0.35 p < 0.05		Ca(meq%)
R ² < 0.35 0.05 < p < 0.1		Ca(mol%)
0.35 < R ² < 0.55 p > 0.1	K(H ₂ O) IC%	

The following Figure 29 shows a biplot of $PC1_{low}$ and $PC2_{low}$ (73% variance) and plant covered as well as water-saturated sites. Measured sites at Martenhoflacke (all P_{uncov}) were again relatively similar and yielded negative results both for $PC1_{low}$ and $PC2_{low}$. At Moschadolacke P_{uncov} site Mo1 showed similarly negative $PC1_{low}$ and positive $PC2_{low}$ values than P_{cov} Mo2 – Mo4 sites. In the subsoil Mo5 was relatively different from other sites with negative $PC2_{low}$ values regardless of P_{cov} status. Water-saturated sites at Illmitzer Zicksee yielded no clear visual difference from other P_{uncov} sites with high positive values of $PC1_{low}$ and unclear dynamics of $PC2_{low}$. Zi5 the only P_{cov} site exhibited lower $PC1_{low}$ values than the other sites. Figure 28 depicts results of $PC1_{low}$ – $PC3_{low}$ at all sites, Appendix Table 8 shows exact numerical results of $PC1_{low}$ – $PC3_{low}$.

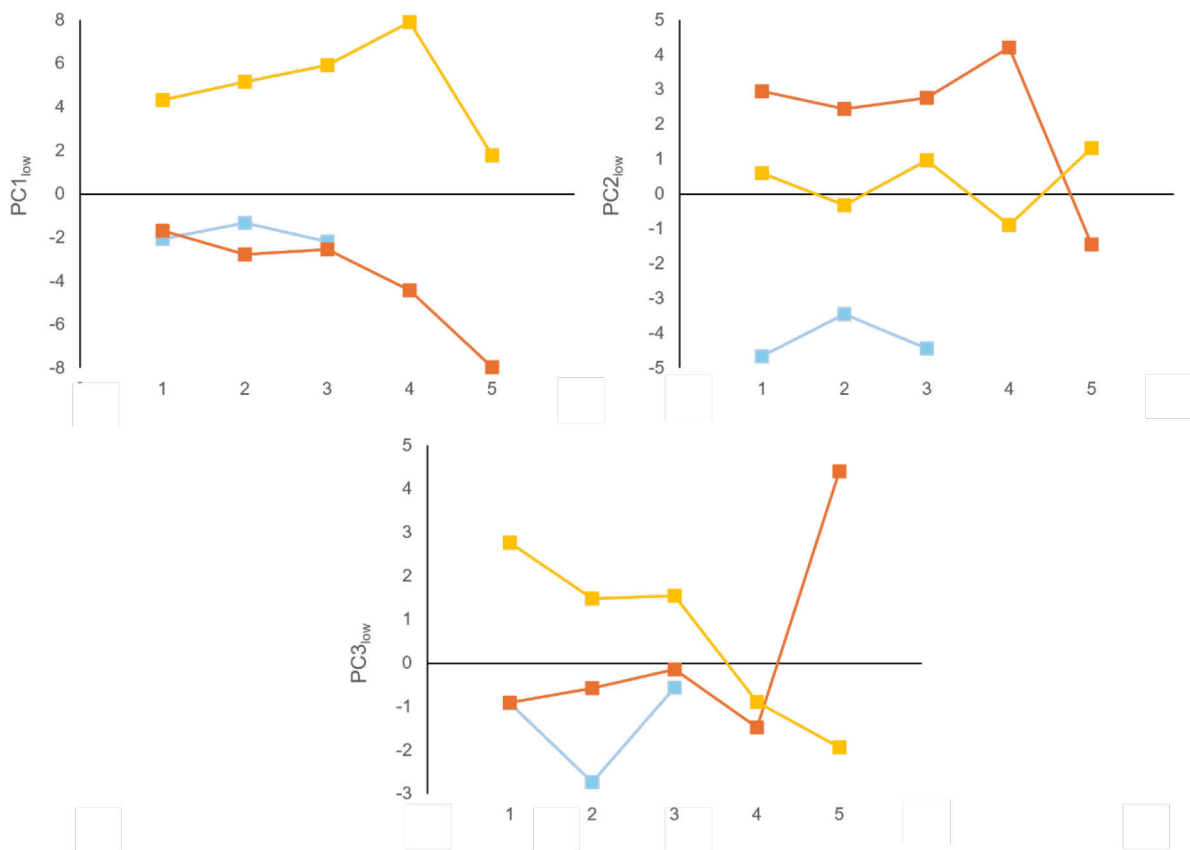


Figure 28: Results of $PC1_{low}$ – $PC3_{low}$ (blue = Martenhoflacke, red = Moschadolacke, orange = Illmitzer Zicksee).

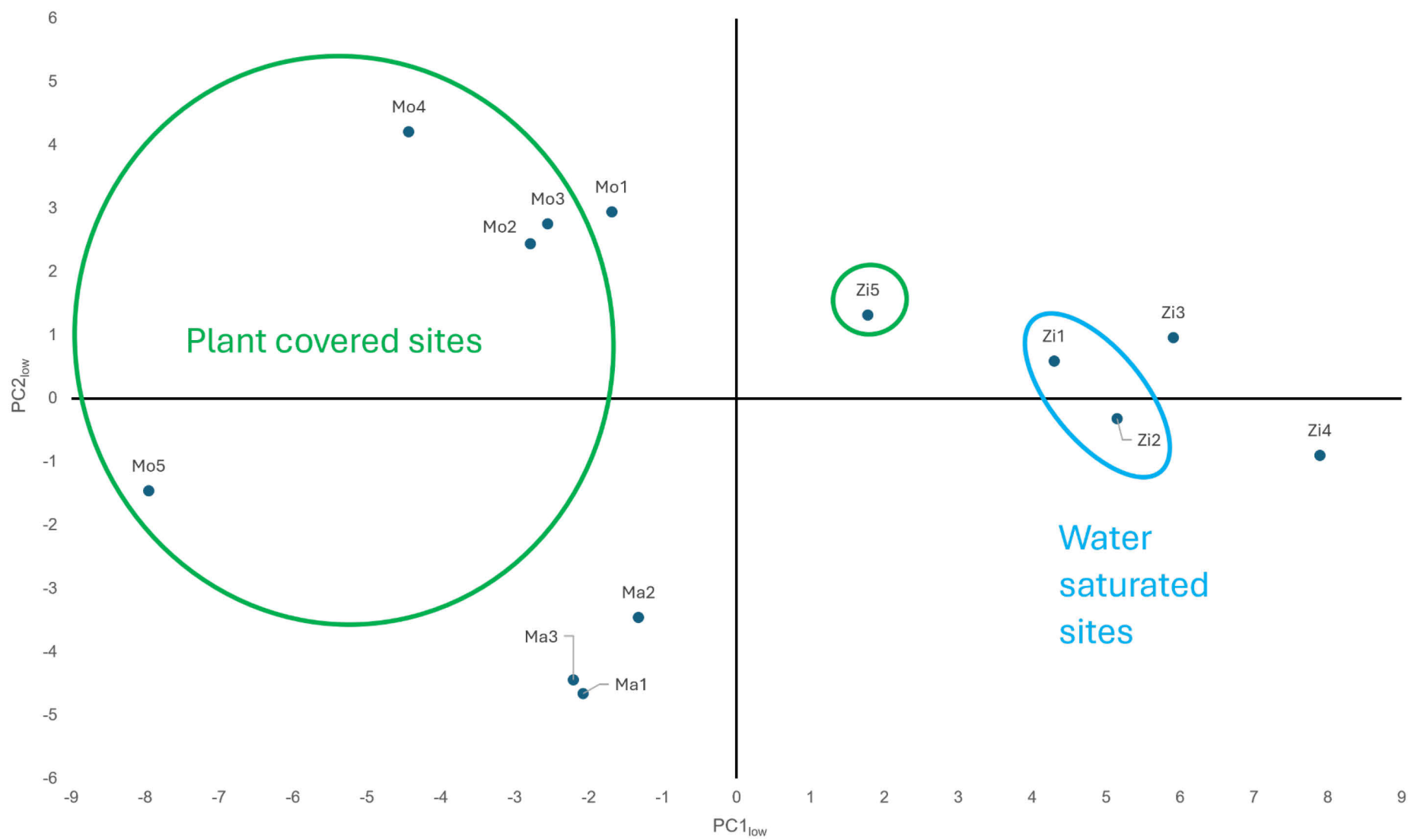


Figure 29: Biplot of PC1_{low} and PC2_{low}.

3.3.4. Correlations: SHC and principal components

Of all principal components, only PC1_{up} ($r = -0.780$, $R^2 = 0.61$, $p < 0.05$) and PC2_{low} ($r = 0.624$, $R^2 = 0.389$, $p < 0.05$) showed significant OLS correlations with transformed SHC (Table 38).

Table 38: Results of OLS-correlations for SHC and principal components ((***): $p < 0.05$).

PC	SHC ~ PC _{up}		SHC ~ PC _{low}	
	r	R^2	r	R^2
1	-0.780***	0.610	-0.321	0.103
2	0.070	0.005	0.624***	0.389
3	-0.006	0.000	0.287	0.083
4	-0.282	0.079		

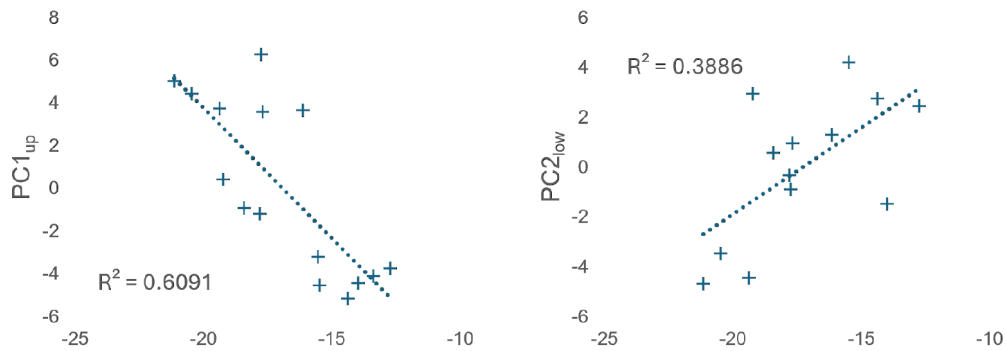


Figure 30: Statistically significant correlations of $\ln(K_{f,10^\circ\text{C}, \text{corr}})$ (SHC, x-axis) and principal components.

3.3.5. Correlations: SHC and topsoil properties

3.3.5.1. PCA examined topsoil properties

The strongest positive correlation of PCA examined topsoil properties and SHC was observed with OC% ($R^2 = 0.775$, $p < 0.05$), while pH yielded the strongest negative correlation ($R^2 = 0.551$, $p < 0.05$). Both Ca(H₂O) and Ca(H₂O%) yielded strong positive correlations with SHC as well. Moderate positive correlations were observed for K(mol%)/K(meq%) and moderate negative correlations were observed for parameters CEC_{eff, AT}, Na(mol%), Na(meq), Ca(meq), CEC_{eff, INT}, Na(meq%), SAR, CROSS and Na(H₂O%). All strong and moderate correlations were highly statistically significant ($p > 0.05$). Table 39 shows OLS correlation results of transformed PCA examined soil properties and transformed SHC, Table 40 summarizes OLS correlation strengths for relevant topsoil properties and SHC. Figure 31 graphically shows strong OLS correlations of topsoil parameters and SHC.

Table 39: OLS correlation results of SHC and PCA examined topsoil properties ((***): $p < 0.05$)

Soil property	r	R ²	Soil property	r	R ²	Soil property	r	R ²
pH	-0.742***	0.551	K(meq)	-0.290	0.084	K(H ₂ O)	-0.505***	0.255
EC	-0.233	0.054	Mg(meq)	-0.376	0.142	Mg(H ₂ O)	0.499**	0.249
sand%	0.161	0.026	Ca(meq)	-0.689***	0.475	Ca(H ₂ O)	0.787***	0.620
silt%	0.072	0.005	CEC _{eff, INT}	-0.678***	0.460	Na(H ₂ O%)	-0.651***	0.424
clay%	-0.500***	0.250	Na(meq%)	-0.589***	0.347	K(H ₂ O%)	-0.062	0.004
CEC _{eff, AT}	-0.686***	0.471	K(meq%)	0.668***	0.447	Mg(H ₂ O%)	0.515***	0.265
Na(mol%)	-0.602***	0.362	Mg(meq%)	0.420	0.176	Ca(H ₂ O%)	0.759***	0.576
K(mol%)	0.690***	0.476	Ca(meq%)	-0.139	0.019	salt _{min} %	-0.424	0.180
Mg(mol%)	0.447**	0.200	SAR	-0.684***	0.468	OC%	0.880***	0.775
Ca(mol%)	-0.010	0.000	CROSS	-0.644***	0.415	IC%	-0.113	0.013
Na(meq)	-0.729***	0.531	Na(H ₂ O)	-0.520	0.270	>2mm%	0.084	0.007

Table 40: Relevant OLS correlation strengths and significance level of topsoil properties and SHC.

Correlation strength	r > 0	r < 0
R ² > 0.55 p < 0.05	OC% > Ca(H ₂ O) > Ca(H ₂ O%)	pH
0.35 < R ² < 0.55 p < 0.05	K(mol%) > K(meq%);	Na(meq) > Ca(meq) > CEC _{eff, AT} > CEC _{eff, INT} > SAR > Na(H ₂ O%) > CROSS > Na(mol%) > Na(meq%)
R ² < 0.35 p < 0.05	Mg(H ₂ O%)	K(H ₂ O) > clay%
R ² < 0.35 0.05 < p < 0.1	Mg(H ₂ O) > Mg(mol%)	

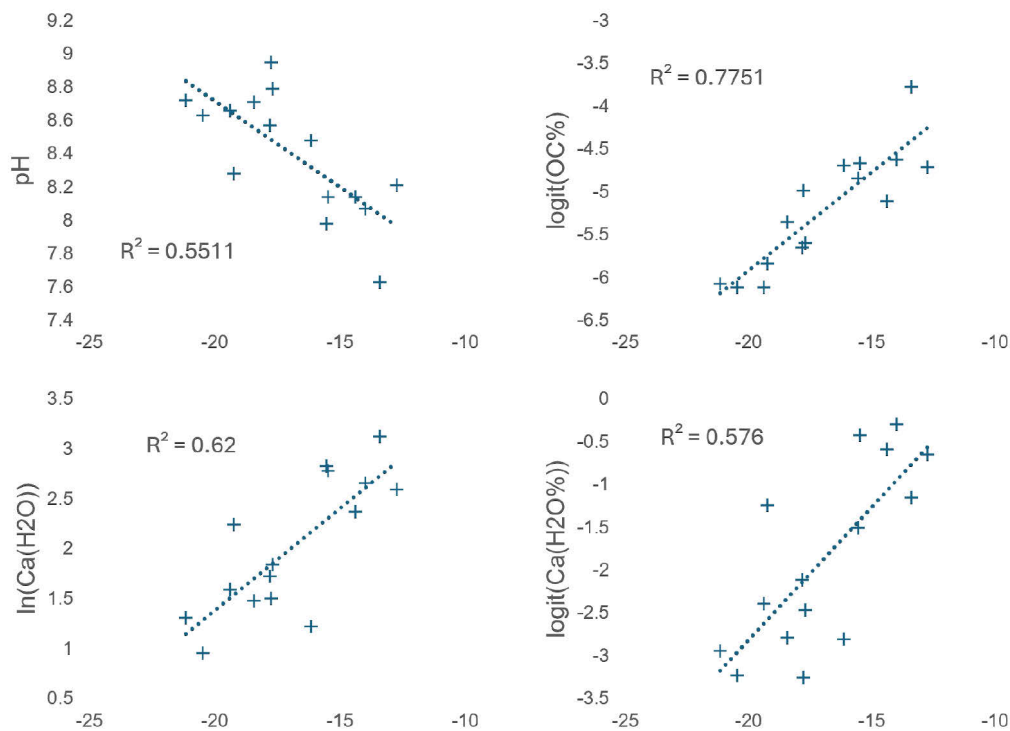


Figure 31: Strong OLS correlations of $\ln(K_f 10^\circ\text{C, corr})$ (SHC, x-axis) and topsoil parameters.

3.3.5.2. Topsoil bulk density and water content

On all measurement sites where BD and WC could be tested, BD showed a moderate negative correlation ($R^2 = 0.479$, $p < 0.05$) with SHC, while WC was not statistically correlated. Furthermore, both BD and WC were not statistically correlated with any PC_{up} .

3.3.6. Correlations: SHC and subsoil properties

Correlation of SHC and subsoil properties yielded the strongest negative correlation for silt% ($R^2 = 0.472$, $p < 0.05$) and the strongest positive correlation for Mg(mol%) ($R^2 = 0.471$, $p < 0.05$). Furthermore, Mg(mol%) as well as Mg(H₂O) also yielded positive, moderate correlations. Table 41 shows OLS correlation results of transformed PCA examined soil properties and SHC, Table 42 summarizes OLS correlation strengths for relevant subsoil properties and SHC.

Table 41: OLS correlation results of SHC and PCA examined subsoil properties ((***): $p < 0.05$; (**): $p < 0.1$)

Soil property	r	R ²	Soil property	r	R ²	Soil property	r	R ²
pH	-0.302	0.091	K(meq)	0.020	0.000	K(H ₂ O)	-0.288	0.083
EC	-0.472**	0.223	Mg(meq)	0.226	0.051	Mg(H ₂ O)	0.598***	0.358
sand%	0.275	0.075	Ca(meq)	-0.012	0.000	Ca(H ₂ O)	0.415	0.172
silt%	-0.687***	0.472	CEC _{eff, INT}	0.016	0.000	Na(H ₂ O%)	-0.569**	0.324
clay%	0.231	0.053	Na(meq%)	-0.548**	0.300	K(H ₂ O%)	0.476	0.227
CEC _{eff, AT}	-0.011	0.000	K(meq%)	-0.041	0.002	Mg(H ₂ O%)	0.580	0.336
Na(mol%)	-0.547**	0.299	Mg(meq%)	0.644***	0.415	Ca(H ₂ O%)	0.479	0.230
K(mol%)	0.123	0.015	Ca(meq%)	-0.257	0.066	salt _{min} %	-0.478**	0.228
Mg(mol%)	0.686***	0.471	SAR	-0.394	0.155	OC%	-0.027	0.001
Ca(mol%)	-0.018	0.000	CROSS	-0.351	0.123	IC%	-0.443	0.196
Na(meq)	-0.268	0.072	Na(H ₂ O)	-0.554**	0.307	>2mm%	0.076	0.006

Table 42: Relevant OLS correlation strengths and significance level of subsoil properties and SHC.

Correlation strength	r > 0	r < 0
0.35 < R ² < 0.55 p < 0.05	Mg(mol%) > Mg(meq%) > Mg(H ₂ O)	silt%
R ² < 0.35 p < 0.1		Na(H ₂ O%) > Na(H ₂ O) > Na(meq%) > Na(mol%) > salt _{min} %

4. Discussion

4.1. SHC in examined soda pans

From the findings of this study, degraded Moschadolacke showed statistically higher SHC across all sites than Martenhoflacke (visible zonation) and Illmitzer Zicksee (water-saturated center). However, Martenhoflacke and Illmitzer Zicksee did not show significant differences, albeit different trends of increasing (Martenhoflacke) or constant (Illmitzer Zicksee) SHC on the examined transects. It must be noted that central, water-saturated areas within Illmitzer Zicksee showed higher SHC than central, non-water-saturated areas within Martenhoflacke (discussed in chapter 4.3).

SHC measurements within soda pans were consistent with findings by Ghobadian, 1966. In his publication, the author measured laboratory water infiltration rates of undisturbed Solontschak-Solonetz soil cores originating from an area near Lange Lacke of $\approx 10^{-3}$ ml/s. Under the assumption of a measurement temperature $\approx 20^\circ\text{C}$ and a hydraulic gradient of ≈ 1 this yields a k_f $_{10^\circ\text{C}}$ of $\approx 10^{-8}$. Similar SHC was measured in Illmitzer Zicksee under field conditions on Solontschak-Solonetz soils.

Lastly, full plant cover within soda pans was observed to increase average SHC statistically significantly by a factor of ≈ 100 across all soda pans. This distinction was most strongly visible at Mo2, which was the only examination site covered by common reed. This increase in SHC might stem from plants creating biopores (e.g., Xiong et al., 2022) and by increasing OC% of the soil (e.g., Kuzyakov et al., 1999). The tendency of increased OC% has been observed for topsoil in this study as well (Table 26). Furthermore, closed plant cover could be a sign for better growth conditions such as lower pH, lower salt content and better soil structure because of lower Na^+ content (e.g., Hailu and Mehari, 2021). These conditions in turn have been shown to be relevant for SHC within this study as well (see below).

4.2. SHC and soil properties

4.2.1. Interpretation of PCA results

4.2.1.1. Topsoil principal components (PC_{up})

$PC1_{up}$ (44% of variance) was strongly, positively correlated with topsoil properties associated with soil dispersivity, such as exchangeable and soluble Na^+ , pH, as well as SAR and CROSS. Strongly negative correlations were obtained with soluble Ca^{2+} . Therefore, $PC1_{up}$ can be described as a measure for soil dispersivity, which is also indicated by high values in Ma1 – Ma3 and for non-flooded sites Zi3 – Zi5, which mostly showed P_{uncov} and saline soil conditions, as well as low SHC.

$PC2_{up}$, which still explained $\approx 23\%$ of the variance of measurement sites, seems to relate to differences in Mg^{2+} and Ca^{2+} saturation as well as IC%. From these results, increases in exchangeable Mg^{2+} are likely to be associated with increases in IC%. This result might be connected to protodolomite formation, which will be discussed in chapter 4.4.1. However, no definitive explanation for this can be developed within this study.

Both $PC3_{up}$ and $PC4_{up}$ only explained a total of $\approx 20\%$ of variance. $PC3_{up}$ seemed to be a factor describing differences in absolute exchangeable K^+ . $PC4_{up}$ already showed diffuse factor loadings, which were slightly influenced by $>2mm$ and silt%.

4.2.1.2. Subsoil principal components (PC_{low})

$PC1_{low}$ ($\approx 56\%$ of variance) showed similar correlations as $PC1_{up}$. However, factors representing relative soluble cation content as well as connected EC and derived $salt_{min}\%$ showed stronger correlations with $PC1_{low}$ than with $PC1_{up}$. Variables representing soil sodicity/stability again showed strong correlations with $PC1_{low}$ as well. While $PC1_{low}$ correlations show similar patterns than $PC1_{up}$, it can be deduced that $PC1_{low}$ represented a more complete picture of soil sodium salinization. This categorization is supported by positive correlations with $Na(meq)$, SAR, CROSS, $Na(H_2O/H_2O\%)$ and most of all negative correlations with relative soluble content of K, Mg and Ca.

$PC2_{low}$ explained $\approx 22\%$ of the variance and showed the highest correlations with soil Mg^{2+} content, indicating a measure of soil exchangeable Mg^{2+} content. $PC3_{low}$, which only explained $\approx 10\%$ of variance, was mostly correlated to silt% and IC%, indicating a measure for loessian sediments, which potentially correspond to a (saline) soil-forming sediment “Schwemmlöss” as described in Husz, 1961.

4.2.2. PCA results and SHC

4.2.2.1. SHC relevant principal components

Of all PCA components, only $PC1_{up}$ showed a satisfying, strongly negative correlation with SHC ($R^2 = 0.61$; $p < 0.05$). This finding is not surprising, considering that $PC1_{up}$ likely measures topsoil stability and dispersivity and includes soil stability indicators derived from soil ion content, such as SAR and CROSS. Plotting $PC1_{up}$ and $PC2_{up}$ in a biplot (Figure 27) revealed that P_{cov} sites generally showed less soil

dispersivity, except for Zi5. A potential reason for P_{cov} at Zi5 might be found in the publication of Franz and Husz, 1961, which stated that some saline horizons in Solontschak/Solonetz soils are covered by a slim layer of sand which supports a plant cover of salt-tolerant grasses. Looking upon water-saturated sites Zi1 and Zi2, indicates that soil stability could not be measured by Na^+ -derived values, likely due to dissolution processes into the free water column. SHC, on the other hand, was similarly low as on non-water-saturated sites Zi3 – Zi5. The difference between $PC2_{up}$ for sites at Martenhoflacke and both other lakes will be discussed in chapter 4.4.1.

$PC1_{low}$, although describing soil sodium salinization, did, however, not show any correlation with SHC. Of all PC_{low} values, only $PC2_{low}$, a measure for soil Mg^{2+} content, showed a moderate, positive correlation with SHC ($R^2 = 0.389$, $p < 0.05$). Findings of low correlations with these factors do not come as a surprise because singular subsoil properties also do not show strong correlations with SHC.

4.2.2.2. Subsoil properties influence on SHC

Consequently, two potential reasons can be identified for soil properties present in $PC1_{low}$ not showing a satisfying correlation with SHC: firstly, because water infiltration depth was insufficient through the topsoil of low to extremely low permeability, conditions in the subsoil did not impact SHC measurements. Secondly, SHC measurements could be influenced by anisotropic vertical water infiltration, which led to topsoil-biased measurements. Both Ghobadian, 1966 and Krachler et al., 2000 report that (healthy) Solontschak/Solontschak-Solonetz soils can dry out substantially in the topsoil (ca. 10 cm) but retain water saturation in the subsoil due to capillary rise of groundwater. These differences might have led to changes in pre-infiltration saturation state and consequent differences in SHC. Furthermore, observations of similar $PC1_{low}$ values in subsoils of Ma1 – Ma3 and Mo1 – Mo3 are contrary to SHC, which was much higher in both Mo2 and Mo3 than in Ma2 and Ma3. Looking upon a biplot of $PC1_{low}$ and $PC2_{low}$ also reveals that water-saturated Zi1 and Zi2 sites were relatively similar to unsaturated sites, indicating no influence of infiltrating water in the subsoil (Figure 29). It seems likely that even if water infiltration reached a certain depth, k_r values of the subsoil would differ much from the topsoil, and vertical flow along the border could occur. This process might be enhanced in soda pans because of their reported stark textural changes in the underlying sediment (Belocky et al., 1998; Häusler, 2023). This textural change can lead to lower water permeability under unsaturated conditions, even if underlying sediments show a rougher soil texture (Li et al., 2014) due to the dynamics described in chapter 1.2. Belocky et al., 1998 reported low permeabilities in coarse-textured layers with high silt content underneath Lange Lacke, while coarse-textured layers on the surface could not be used as predictor for high permeability of underlying (impermeable) sediments.

While this study cannot fully explain subsoil importance for SHC within soda pans, topsoil properties showed satisfactory correlations particularly if dimensionality was reduced through PCA. In the following section of the discussion, if not specified differently, topsoil properties shall be discussed, since their influence was more definitive on measured SHC.

4.2.3. Organic Carbon OC%

Within this study, topsoil organic carbon (OC%), although only moderately correlated with PC1_{up}, was by far the best singular, negatively correlated predictor for SHC ($R^2 = 0.775$, $p < 0.05$) in examined soda pans. Considering OC% as a parameter that describes various environmental conditions in one variable might give a better overview of both central, saline soil and border, non-saline soil areas' SHC in soda pans:

Enrichment of OC% is closely linked to plant cover (Kuzyakov et al., 1999), whereby plant cover is a main driver of increasing OC% in soils, particularly under water-saturated conditions (Xiao et al., 2025). Increased OC% could also be observed on P_{cov} sites in this study (Table 26). In theory, this would lead to the formation of an organic layer on the lakebed of the soda pan as observed in non-saline water bodies (Kirschner, 2007). However, Krachler et al., 2000 hypothesized that through floating particles caused by turbidity enhanced by pH and wind, oxygen availability for remineralization of particles is improved. Krachler and Krachler, 2007 found that after drying out, organic matter decomposes relatively fast in an intact soda pan, whereby no significant accumulation of OC% could be detected. High pH might indeed facilitate the remineralization of organic matter during dry-out events (Neina, 2019). Due to relatively slow accumulation times of OC% (Bell et al., 2021; Yang et al., 2016), this parameter might give an overview of the degradation status of saline soils/soda pans. OC% can then be used as a proxy for improved soil stability (Benjamin et al., 2008) as well as (reduced) BD (Adams, 1973), which has been found influential for SHC as well within this study. Moreover, several studies show that water retention capacity increases with increasing OC%, likely due to improved soil stability (Lal, 2020; Panagea et al., 2021). On Solontschak-Solonetz soils with extreme water conditions throughout the year (Ghobadian, 1966), this might improve plant growth. Differences in WC and OC% at Ma3 and Ma4 indeed suggest this connection within the study as well. Therefore, SHC might increase with OC% enrichment in soda pans partly due to improved plant growth.

In this context, Ma5 as an outlier because of very high OC% must be examined because of high SHC, very low WC and resulting special cation and pH dynamics on this site (see discussion below). Exceptionally low WC might have been an explanation for highly increased OC% on this site. Dryland carbon fluxes are complex and are highly dependent on water availability for microbial decomposing activity (Waring et al., 2021), which is also one of the reasons for chernozem organic matter accumulation (Nestroy et al., 2011). Site Ma5 functions as an absolute carbon sink because of a relatively dry and warm climate combined with very shallow soil (no subsoil sampling possible) on a well-drained site indicated by highest topsoil >2mm% content and high SHC. The comparably low pH on this site might have further favored OC% increases (Kabelka et al., 2025; Kuśmierz et al., 2023).

When looking at all other measurement sites, OC% values in examined soda pans were low compared to soils in central Europe (Blume et al., 2010). These low values have been reported for intact Solontschak(-Solonetz) soils. Furthermore, the supposed pedogenetic development of Solontschak soils under lower groundwater levels towards Solonetz also seemingly increases OC% in the topsoil when looking at the

OC% of typical profiles (Franz and Husz, 1961; Nelhiebel, 2001). Findings indeed show that OC% did not change much in central, mostly Solontschak-Solonetz areas of the soda pans; however, OC% was slightly higher in supposedly intact Solontschak-Solonetz soils in Illmitzer Zicksee than in Martenhoflacke and Moschadolacke. A potential reason for this might be the use of Illmitzer Zicksee, as a wastewater dumping ground by neighboring communities which might have changed growth conditions, and led to dense reed cover on $\approx 40\%$ of the lake (Krachler et al., 2012). Dense reed cover has been hypothesized to further reduce turbidity by wind shielding and subsequent growth of an organic layer on lake beds of soda pans, particularly if no total dry out occurs (Krachler et al., 2000).

4.2.4. Soil ion content, pH and EC

Relative and absolute topsoil soluble Ca^{2+} were the most important cationic soil properties correlated positively with SHC ($\text{Ca}(\text{H}_2\text{O})$: $R^2 = 0.620$, $p < 0.05$; $\text{Ca}(\text{H}_2\text{O}\%)$: $R^2 = 0.576$, $p < 0.05$) within this study. From a literature perspective, this comes as no surprise, as high Ca^{2+} content of infiltrating solutions stabilizes the soil by aggregation of particles even at very low concentrations (Shainberg and Letey, 1984). Furthermore, soluble Ca^{2+} can also be attributed to lower pH due to the dissolution of CaCO_3 (Al Omari et al., 2016), which has been found in substantial quantities within examined soda pans (IC%: Table 27). Lower pH on the other hand, might be positively correlated with P_{cov} because of additional acidification through root acids (Vives-Peris et al., 2020) and better growth conditions on non-alkaline sites. On the contrary, high pH has been traditionally connected to Sodium salts such as NaHCO_3 or NaCO_3 in Austrian soda pans (Krachler and Krachler, 2007) and saline soils (Nestroy et al., 2011). Since pH is a logarithmic value, minor changes in pH lead to drastic changes, as observed in Moschadolacke, which, albeit still relatively high pH in the topsoil, does not exhibit an unvegetated surface over much of the lakebed. Alkalinity of soil arguably reduces SHC by increasing the negative surface charge and therefore increasing absolute zeta potential (see chapter 1.3) and therefore dispersivity. This connection of SHC and pH has been shown within this study as well, whereby topsoil pH showed the strongest negative correlations of all singular parameters with SHC ($R^2 = 0.551$; $p < 0.05$). Furthermore, topsoil exchangeable Na^+ showed moderate correlations with SHC both absolutely ($\text{Na}(\text{meq})$: $R^2 = 0.531$, $p < 0.05$) and relatively (e.g. $\text{Na}(\text{meq}\%)/\text{ESP}$: $R^2 = 0.347$, $p < 0.05$). The same held true for topsoil relative soluble Na^+ ($\text{Na}(\text{H}_2\text{O}\%)$: $R^2 = 0.424$, $p < 0.05$). As described in chapter 1.3.4 at $\text{ESP} < 15$, soil dispersion is the dominating process in SHC reductions. Only at higher ESP levels does clay swelling become dominant over clay dispersion, if expandable smectite-type clay minerals reach sufficient quantities within the soil (Shainberg and Letey, 1984).

Both high $\text{Na}(\text{meq}\%)/\text{ESP}$ (> 15) and smectite-type clay minerals could only be expected for sites Zi4 and Zi5. On the other sites in Illmitzer Zicksee, although smectite-type clay minerals could be expected, (recent) water saturation reduced exchangeable Na^+ below the swelling threshold. The other soda pans did not contain smectite-type clay minerals at the central measurement sites, which were instead dominated by illite and chlorite. This might also explain why topsoil relative exchangeable Ca^{2+} was not correlated with SHC: In their literature review, Shainberg

and Letey, 1984 summarized that small quantities of exchangeable Na^+ are enough to increase soil dispersivity because Na^+ cations are more likely to adsorb to the outer areas of clay minerals and therefore exert high influence on clay surface zeta potentials. This is of course also dependent on clay mineralogy, whereby illite disperses more easily than smectite at lower ESP levels because of surface differences. Exchangeable Ca^{2+} , on the other hand, seems to be more important in swelling processes, because of lower swelling pressure as opposed to exchangeable Na^+ (Blume et al., 2010). However, if swelling is not the main process to reduce SHC, Ca^{2+} at the exchange sites becomes only relevant if it displaces Na^+ , as observed in Ma5 (see below).

In the case of topsoil absolute and relative soluble Na^+ , better correlations with pH and SHC could have been established if the outlier at Ma5 had not been measured. At Ma5, $\text{Na}(\text{H}_2\text{O}/\text{H}_2\text{O}\%)$ remained high, while exchangeable and soluble Ca^{2+} increased and pH decreased. Furthermore, SHC and OC% were highly increased and WC was very low on this site. This observation points towards a complex interplay of numerous factors on this site: Precipitation followed by decomposition pulses (Waring et al., 2021) might partly explain a decreasing pH through the release of humic acids, which can be observed in composting processes (Gao et al., 2010; Yang et al., 2013). This in turn might lead to the formation of humic acids and form complexes with cations such as sodium (Tan et al., 2019). Sodium humate, a salt from humic acid and Na^+ shows decreasing solubility under lower pH (Melo et al., 2016), as opposed to a good solubility of NaHCO_3 in water (National Center for Biotechnology Information, 2025) and an acid-base reaction releasing Na^+ under low pH conditions. The consequent change in soil salt composition might explain why soluble Na^+ at Ma5 was not predicting high pH, because of its missing connection with alkaline HCO_3^- . The formation of humic acids and of “Sodium humate” has indeed been proposed for Austrian saline soils as a way of organic matter transport in the subsoil via soil cracks (Franz and Husz, 1961). Further examinations of the distribution of potential counterions for Na^+ , and their respective effects, are necessary to confirm this hypothesis. Furthermore, increased soluble Ca^{2+} and decreased contents of Na^+ at the exchange sites could be observed, visible on this site in the ratio of exchangeable Na^+ (3.5 meq-%) and Ca^{2+} (78.2 meq-%). This points towards the substitution of exchangeable Na^+ with Ca^{2+} on this site.

Relative exchangeable topsoil K^+ showed moderately positive (e.g. $\text{K}(\text{mol}\%)$: $R^2 = 0.476$, $p < 0.05$) correlations with SHC, while topsoil $\text{K}(\text{meq})$ was uncorrelated to SHC. As described in chapter 1.3, particularly the influence of K^+ can be negative because of its ionicity and related increases in ζ -potentials. In this study, however, a higher relative K^+ concentration at the exchange sites was positively correlated with SHC. This might be explained by higher relative exchangeable K^+ in Moschadolacke, the soda pan with the highest overall SHC. This degraded soda pan likely is well-drained, indicating a shift from easily extractable Na^+ to K^+ in relative terms. This effect is also visible in (recently) flooded sites at Illmitzer Zicksee (Zi1 – Zi3), which exhibit lower relative Na^+ , while $\text{K}(\text{mol}\%/\text{meq}\%)$ remained on similar relative levels when compared to Zi4 – Zi5. Relative exchangeable topsoil Mg^{2+} only showed weak correlations with SHC. In the subsoil, however, exchangeable Mg^{2+} showed the strongest positive correlations with SHC (e.g. $\text{Mg}(\text{mol}\%)$: $R^2 = 0.471$, $p < 0.05$). This connection was likely measured because of higher $\text{Mg}(\text{mol}\%/\text{meq}\%)$ in Moschadolacke and Illmitzer

Zicksee, as opposed to Martenhoflacke (lowest overall SHC). As discussed in chapter 4.4.1, this difference might stem from protodolomite formation within these lakes.

The missing effect of exchangeable K^+ and Mg^{2+} is also visible in the correlations of SHC with topsoil SAR and CROSS. Topsoil SAR showed slightly stronger negative correlations with SHC ($R^2 = 0.468$, $p < 0.05$) than topsoil CROSS ($R^2 = 0.415$, $p < 0.05$), likely due to the K^+ dynamics described above. This indicates a better suitability of SAR than CROSS for comparing changes in SHC induced by soil exchangeable ion content across Austrian soda pans.

Both topsoil $CEC_{eff, AT}$ and $CEC_{eff, INT}$ showed moderate, negative correlations (e.g. $CEC_{eff, INT}$: $R^2 = 0.46$, $p < 0.05$) with SHC. Several studies report the connection of clay%, soil mineralogy, OC% and pH with CEC_{eff} across a wide range of soils (Manrique et al., 1991; Martel et al., 1978; Wilding and Rutledge, 1966). Within these studies, the contribution of OC% to CEC_{eff} is usually significant, which is surprising considering the relatively high negative correlations with SHC obtained within this study. If OC% contributed strongly to CEC_{eff} , one would expect the opposite, or at least only weak negative correlations with SHC. Within this study, high correlations of both CEC_{eff} values might be explained by the calculation of CEC_{eff} as the sum of basic cations, which may be influenced by an overestimation of Ca^{2+} , particularly under the influence of high pH (Rutter et al., 2022). Other cations, such as Al^{3+} and H^+ , which were not explicitly measured, are believed to be of low influence for CEC_{eff} at high pH (Ross and Skjellberg, 2023). Due to missing instrumental capacities for measuring the exchanged Ba^{2+} , no CEC_{total} could be measured. In theory, CEC_{total} could be calculated and related to CEC_{eff} to determine the, likely substantial, influence of soil salinity on CEC_{eff} . Findings of this study show that particularly in the topsoil, CEC_{eff} was the highest in saline soil, except for water-saturated sites Zi1 – Zi2. Therefore, both CEC_{eff} values might have been a measure for soil salinity and SHC reductions, however, future studies must be conducted to develop a relationship between CEC_{eff} and CEC_{total} in Austrian saline soils.

Lastly, EC might not have been relevant for SHC because correlations were calculated across Solontschak-Solonetz and other less dispersive soil types, which in turn might have led to less pronounced results of some parameters, which are mostly important for SHC in dispersive soils. Moreover, because EC_e could only be estimated by $EC(2:3)$, the real EC of the percolating solution might highly differ due to specific solution conditions. For instance, in their examination of saline soil profiles in Austrian soda pans, Nelhiebel, 2001 found topsoil EC_e values of 108 mS/cm, as opposed to an $EC(1:10)$ of 2170 μ S/cm. This points towards the non-linear relationship of diluted EC and EC_e and shows that EC_e has to be measured to further examine the influence of soil soluble ion content on SHC.

4.2.5. Bulk density (BD) and soil gravel content (>2mm%)

Topsoil BD showed a medium, negative correlation strength ($R^2 = 0.479$; $p < 0.05$) with SHC. This is unsurprising considering BD has been shown to influence SHC (Assouline, 2006; Perrone and Madramootoo, 1994). Furthermore, BD likely

summarizes the influence of several parameters, such as soil compaction, soil gravel content >2mm%, and fine soil texture, as well as soil mineralogy:

Of particular interest in terms of BD are the central areas of Moschadolacke Mo1 and Mo2, which were influenced by human digging activities and exhibit stark differences in BD as well as SHC when compared to the rest of the lake. BD at Mo1 was amongst the highest in all examined soda pans, while Mo2 exhibited the lowest BD of all soda pans. It is reasonable to assume that through excavation at Mo1 and subsequent deposition of material at Mo2 (indicated by absolute height differences), BD was changed through human activity. At Mo1, material was excavated to create a basin for hunters (Krachler et al., 2012), and subsoil layers are now forming the surface, whereby it is well-established that subsoils with similar properties can have higher BD than topsoils through compaction (Blume et al., 2010; Perrone and Madramootoo, 1994). Furthermore, heavy excavating machinery might have further compacted soils at Mo1, and the site shows highly increased >2mm%, which might have caused higher than usual BD and slightly increased SHC (compared to similar sites Ma1 – Ma3) as well (see paragraph below). On the other hand, at Mo2, deposition of material might have led to the emergence of reed because soils were more suitable for reed growth and competition with other plants was reduced. Through its rhizomes, reed might have stabilized low BD at Mo2 or decreased BD even further, although limited observations are reported on this process (Gucker, 2008).

Moreover, it is of interest to look at BD dynamics in Martenhoflacke, whereby similar sites of Solontschak-Solonetz Ma1 – Ma3 as well as non-saline soil sites Ma4 and Ma5 can be compared. First, from Ma1 to Ma3, SHC and BD gradually increased, although parameters should have been negatively correlated from the findings of this study. At the same time topsoil WC and sand% decreased while topsoil clay% remained relatively stable. These findings are again surprising considering higher WC at similar clay% would normally show higher pore volume and decreased BD (Blume et al., 2010). A potential reason for differences in BD and consequently SHC might be found in soil gravel content: While soil gravel content (>2mm%) did not show a significant correlation with SHC, it is possible to explain differences between SHC and BD in Martenhoflacke using this parameter: While between Ma1 and Ma2 no increases in >2mm% could be measured, Ma3 already exhibited increased gravel content. Since gravel content decreases the total pore volume and (quartz) gravel has a higher density than fine-packed soil, also, BD might increase as found by Rücknagel et al., 2013. At the same time, while total pore volume might have been reduced, pore volume and macropores could be increased through imperfect soil particle packing (Beck-Broichsitter et al., 2023), which might lead to higher SHC. The difference in >2mm% content could also explain why BD is as high in Ma4 as in Ma3, even though SHC, OC%, and WC are larger at this site. Ma4 already exhibits high >2mm%, whereby BD might remain high through high quartz density. At Ma5, BD decreases sharply, potentially because gravel volume increased above a soil specific threshold, at which BD decreases again. Moreover, low-density organic matter was highly increased, pointing towards a decreased fine soil BD. This in turn can partly explain a relatively high, relative salt weight ($\text{salt}_{\min}\%$) at Ma5

Differences in >2mm%, however, cannot explain why Ma1 and Ma2 do exhibit BD that is higher than on similar unflooded sites Zi3 and Zi4. The following chapters will discuss

soil mineralogy differences and fine soil texture's potential influence on BD as well as SHC.

4.2.6. Soil and clay mineralogy

Soil and particularly clay mineralogy in Austrian soda pans is a central topic because, (1) SHC is highly influenced by clay dispersive behavior and ζ -potentials, as well as (2) deep shrinkage cracks in Austrian saline soils are hypothesized to form readily (Nestroy et al., 2011), potentially leading to preferential flow. Furthermore, (3) the authigenic formation of clay minerals such as smectites and protodolomite (Krachler and Krachler, 2007), as well as the SHC reducing attributes of fine clay particles within saline soils (Krachler et al., 2012) have been postulated. The latter shall be discussed in chapters 4.2.7 (importance of fine soil texture) and 4.4.1 (authigenic mineral formation).

A clay mineralogical examination by Gritzmann and Dober, 2014 found high contents of illite and chlorite within samples of soda pans across the Lackenzone, while smectite was not found in every examined "saline horizon" within soda pans ($n_{\text{examined}} = 9$; $n_{\text{smectite}} = 4$). Within this study, the presence of smectite could be confirmed for Illmitzer Zicksee at site Zi1. At Martenhoflacke and Moschadolacke (Ma1 and Mo1) no smectite was found, both in the upper and subsoil. Illite and chlorite, as well as protodolomite, were present together with small quantities of kaolinite, as could be expected from the results of Gritzmann and Dober, 2014 in all three lakes. Martenhoflacke, however, showed lower contents of protodolomite in the clay fraction. This finding has important implications for SHC in examined soda pans: First, SHC might have been influenced by differences in clay mineralogy, which in turn influenced BD and dispersive behavior of soils. It has indeed been published that smectites ($2.0 - 2.6 \text{ g/cm}^3$) have a lower density range than illites ($2.6 - 2.9 \text{ g/cm}^3$) and chlorites ($2.6 - 3.3 \text{ g/cm}^3$) (Deer, W. A., FRS et al., 2013), consequently BD might have been reduced in saline soils containing smectite within Illmitzer Zicksee as opposed to Martenhoflacke. Furthermore, from published CTC of NaHCO_3 on Na^+ -enriched illite (185 meq/l) and smectite (28 – 60 meq/l) (Arora and Coleman, 1979), it becomes apparent that flocculation during SHC measurements might occur more readily in Illmitzer Zicksee as opposed to Martenhoflacke. In central Martenhoflacke, soil would therefore stay impermeable also at higher salt concentrations. This finding could explain why SHC in Zi3 and Zi4 was slightly higher than under similar conditions at Ma1 and Ma2, if smectite content reduced overall BD and decreased CTC, which might have been at least partially reached in high EC soils at Illmitzer Zicksee.

In their conceptual hydrological functioning model of soda pans, Krachler and Krachler, 2007 hypothesize that in the summer, shrinkage cracks form, which increase SHC in soda pans during this period. They report that shrinkage cracks already form when the water becomes clear and sediment flocculates (and CTC is reached). Similar results have been published for the shrinking behavior of kaolinite under high EC (Cai et al., 2023). The assumption of deep and pronounced shrinkage crack formation in all Solontschak/Solonetz soils alike cannot be corroborated by the findings of this study. Earlier results showed that when comparing total clay and montmorillonite/smectite

content, the latter was more influential for clay swelling (Reddy et al., 2020). While all clays swell, particularly smectite clays seem to be responsible for deep and pronounced shrinkage cracks (Elhassan et al., 2023). Consequently, deep shrinkage cracks can be expected if smectite is present, which could not be confirmed for all examined soda pans in the study of Gritzmann and Dober, 2014 and for both Martenhoflacke and Moschadolacke in this thesis. Pictures of soils at Ma2 (WC = 18%) Zi3 (WC = 19%) and Zi4 (WC = 18%) indeed suggest that shrinkage cracks do form more readily in Illmitzer Zicksee (Figure 25). Through these shrinkage cracks SHC, after drought spells in soda pans, which contain smectite, such as Illmitzer Zicksee, might be much enhanced through preferential flow until soil cracks close under increased water saturation through clay swelling. At Martenhoflacke and in an undrained Moschadolacke, on the other hand, low SHC would be maintained also if sediments dry out, because their clay mineralogy prevents extensive shrinking. Subsequently, these lakes might react faster to precipitation after a long drought spell, because of reduced preferential flow under unsaturated conditions.

4.2.7. Fine soil texture

Particularly in groundwater studies, soil texture is considered an important parameter that influences SHC mainly due to pore diameter (see 1.2). In soils, the influence of different fine soil texture classes on SHC strongly varies, as indicated in Table 2. Within this study, a finding by Bargués-Tobella et al., 2024 could be confirmed: namely that pH and OC% were more strongly correlated with SHC than both clay% and sand%. For clay% and pH, negative correlations in an approximate relation of 1:2 (R^2 (clay ~ SHC): 0.25 and R^2 (pH ~ SHC): 0.55) were observed, similar to the above-mentioned study. Sand%, however, did not show any correlation with SHC and was highly variable across study sites. High variability of soil texture components can be expected if soil forming sediments were indeed deposited by fluvial processes as indicated in current theories on soda pan formation (chapter 1.4).

Considering the results discussed above, combined with lower-than-expected SHC in loamy soils in Ma1 – Ma3, it seems as if soil stability/dispersivity rather than differences in soil micropore diameter governed by fine soil texture, were the main drivers of SHC reductions. However, low, albeit significant, correlations with clay content might also stem from accompanying reductions in pore diameter. This might also be a result from differences in liquid and plasticity limits as described by Atterberg, although clay mineralogy also influences these parameters (Elhassan et al., 2023).

Subsoil silt%, which showed a negative, moderate correlation with SHC ($R^2 = 0.472$; $p < 0.05$), likely is not a direct causation, because topsoil silt% did not show any correlations with SHC. Instead, high silt% in subsoils of Moschadolacke might have resulted in relatively strong correlations because of overall high SHC in this soda pan.

4.3. SHC, water saturation and elevation

Two hypotheses were formulated within this study, focusing on whether SHC decreases in lower elevation, central areas of soda pans and whether any connection between SHC and water saturation of a soda pan can be shown. Since both hypotheses are connected, they shall be discussed in the same chapter:

It was indeed found that central, lower elevation areas within soda pans exhibited low SHC, as could be expected if groundwater levels and capillary rise play an important role in impermeable saline soil formation and persistence (Franz and Husz, 1961; Nestroy et al., 2011). However, dynamics were very different across examined soda pans: At Martenhoflacke, SHC indeed showed almost exponential increase from lower to higher elevation areas of the lake. At the same time, particularly for the Solontschak-Solonetz areas Ma1 – Ma3, topsoil WC decreased while SHC increased. A decrease in WC can be explained by increasing elevation and, consequently, less capillary rise of groundwater, or more generally, because (summer) rainwater is collected in lower elevation areas. Both Ma1 and Ma2 exhibited an elevation difference of only 4 cm and relatively homogeneous conditions. However, WC at Ma2 was already reduced by $\approx 4\%$ when compared to Ma1. At Ma3 at an elevation difference of ≈ 10 cm WC was already reduced by 14%. Furthermore, calculated $\text{salt}_{\min}\%$ as well as $\text{Na}(\text{meq}\%)$ was decreased as well. This supports the notion that, at least to a certain degree, capillary rise is responsible for differences in WC. Nevertheless, the limited, patchy, plant cover at Ma3 might have further reduced WC of soil by plant water extraction (Nielsen and Vigil, 2018). At Ma4 and Ma5 no saline soil conditions prevailed and increasing SHC, as well as OC% were observed indicating less ground- or surface water influence, due to elevation differences of +28 cm and +74 cm respectively.

The situation at Illmitzer Zicksee was different: Average SHC was similarly low from Zi1 – Zi5, even though elevation increased by 68 cm. While topsoil WC could not be measured at Zi1/Zi2, WC from Zi3 to Zi5 only decreased from 19% to 16%. While higher WC at Zi3 could still be explained by recent water saturation, at Zi4 ($\text{Zi3} - \text{Zi4 } \Delta_{\text{elevation}} > 10\text{cm}$) WC remained high and calculated topsoil $\text{salt}_{\min}\%$ and $\text{Na}(\text{meq}\%)$ was highest across all measurement sites. This indicates higher relative groundwater levels at Illmitzer Zicksee than at Martenhoflacke, and supports the notion of potential groundwater contributions to Illmitzer Zicksee in the past (Krachler et al., 2012). However, the relative uniformity of an upper groundwater layer particularly under Illmitzer Zicksee is questionable considering the hypothesis and measurements of Häusler, 2023. This matter is discussed in chapter 4.4.2.

Lastly, Moschadolacke did not exhibit clear SHC dynamics, which is likely caused by human surface alterations. Furthermore, groundwater levels at Moschadolacke are likely very low, due to water drainage. Examined topsoil and subsoil properties also did not indicate capillary rise of saline groundwater; instead, high relative exchangeable K^+ and Mg^{2+} contents, as opposed to the other cations, hinted at ongoing leaching of cations. By comparing elevations, however, Moschadolacke showed the least difference of all soda pans, with only a +28 cm difference between artificially excavated Mo1 and Mo5, which had an aerial distance of ≈ 150 m. This also shows that excavations within this soda pan were shallow and likely did not remove a big part of the saline horizon, which is considered the primary source of salt in soda pans. On the

contrary, following capillary rise and assuming a critical groundwater depth of $\approx 2\text{m}$ is necessary for the formation/persistence of topsoil salinization (Chang et al., 2025) a shallow topsoil excavation would support the persistence of a saline soil while groundwater levels are decreasing.

Comparing the low elevation distances at Moschadolacke with Martenhoflacke, similar aerial distances between Ma1 – Ma5 and Mo1 – Mo5 were observed. Nevertheless, the elevation difference was $\approx 70\text{ cm}$ as opposed to $\approx 30\text{ cm}$. If Moschadolacke would not have been drained, under natural conditions, this would indicate a relatively large saline-soil area of little to no vegetation cover and low SHC. By further comparing Martenhoflacke and Illmitzer Zicksee, it is immediately apparent that SHC is lower overall in central areas of Martenhoflacke as opposed to Illmitzer Zicksee. Nevertheless, Martenhoflacke does not exhibit a free water table within the lakebed. From a perspective that solely focuses on SHC, this observation is surprising. In this case, the singular observation of SHC cannot explain why Illmitzer Zicksee maintained a free water table and Martenhoflacke was (mostly) dried out over the examination period. Consequently, other factors that drive water saturation within soda pans must be identified to explain this phenomenon. As Steiner, 2006 already mentioned for all soda pans, a potential reason for water saturation in Illmitzer Zicksee might be found in the form of its lake bed, which is also equal to its catchment areas, as is usually the case in Austrian soda pans. Illmitzer Zicksee has a lakebed almost 30x larger and its (potential) free water area is only 25% of the lakebed as opposed to $>50\%$ in Martenhoflacke (Table 3). Furthermore, the water table height in Martenhoflacke is shallower with only $\approx 10\text{ cm}$ height difference and $\approx 100\text{m}$ between Ma1 and Ma3. At Illmitzer Zicksee the absolute height difference between Zi1 and Zi3 is $\approx 25\text{ cm}$ at $\approx 160\text{m}$ ($\approx 15\text{ cm}/100\text{ m}$). Consequently, evaporation seems to be another important driver for reduced times under water saturation particularly in shallow and small soda pans.

This raises the question of the past and future behavior of free water tables, particularly in small and shallow soda pans such as Martenhoflacke and Moschadolacke. For example, a study of Soja et al., 2013 found that evaporation calculated by the Dalton method during summer months June, July and August (301 mm) was indeed higher than precipitation (225 mm) in the years 1978 to 2010 at the station Neusiedl/See. For Lake Neusiedl, a study of Eitzinger et al., 2009 predicts a $\approx 22\%$ increase in evaporation for the period 2030 – 2050 as opposed to 1961 – 1990. Soja et al., 2013 further hypothesized that evaporation might be higher than precipitation during spring in 2050 as well. In the case of Martenhoflacke, this would mean less time under full water saturation, even if groundwater levels and saline soil dynamics would be maintained within the lake. It also remains an open question how these soda pans behaved hydrologically in the past before drainage of the area started, particularly regarding the persistence of free water tables. This might be also relevant for zonation of the lakes since free water tables arguably are enhancing microbial activity through large surface areas created by turbidity in alkaline water and how salt was transported and deposited within the lakebed (Krachler and Krachler, 2007).

4.4. Further considerations

4.4.1. Authigenic mineral formation in soda pans

The results of clay mineralogy in the examined soda pans have further implications for theories regarding saline soils and SHC. Namely, the authigenic formation of minerals such as smectite from silicic acid, as well as the formation of protodolomite or other carbonates (Franz and Husz, 1961; Ghobadian, 1966; Krachler and Krachler, 2007). Krachler and Krachler, 2007 even hypothesized that the authigenic formation of these minerals have created an impermeable soil layer. While these issues cannot be discussed in detail, the results of this study give limited insight into the applicability of these theories:

Smectite, a group of minerals that may form from silicic acid (a weathering product) in soda pans, has only been found in Illmitzer Zicksee, while protodolomite has been present in all examined clay fractions, although reduced quantities have been found in Martenhoflacke. As stated in chapter 4.2.6, smectite is not known from all soda pans, which would be expected if such authigenic formation of clay minerals occurs in all saline soils. A potential reason for this disparity might be differences in pH, which have been reported to reach values as high as 11 in some places (Franz and Husz, 1961). Bristow et al., 2012 mentions that most clay minerals examined in their study (including smectite) form at pH ≈ 9 . Measured pH levels in the subsoil of Illmitzer Zicksee were indeed much higher (>9) than pH levels in the subsoil of Martenhoflacke ($\approx 8.5 - 8.75$). Relatively dry topsoil at Zi4 also showed higher pH (≈ 9) than found in dry sites Ma1 – Ma3 ($\approx 8.5 - 8.75$). Consequently, either pH values in some soda pans were too low to form smectite authigenically, or smectite has been deposited differently in soda pans. This finding has another important implication, because pH levels could not be higher than this level in Martenhoflacke in the past, otherwise smectite would have formed if pH indeed was the limiting factor.

At Illmitzer Zicksee, the origin of smectite might also be found in Lake Neusiedl, because of the alleged connection of both water bodies in the recent past, supported by historical maps (Krachler et al., 2012). This finding supports the theory of (some) soda pans forming through cut-off from Lake Neusiedl, where both smectite and protodolomite have been found (Neuhuber et al., 2024; Zünterl et al., 2015). In their study, Neuhuber et al., 2024 investigated protodolomite formation in Lake Neusiedl and found that the age of small protodolomite particles $<0.2\mu\text{m}$ in the clay fraction was relatively young (≈ 200 years). Furthermore, crystallization of protodolomite likely occurred in the water column and not in the sediment because of differences in carbonate phase saturation which prevent the solution of high-Mg-carbonates and recrystallization to protodolomite in the buried sediment. These differences might stem from lower pH in the sediment ($7.5 - 8.8$) than in the water column ($8.7 - 9.2$). Findings also suggested a very low sedimentation rate due to flat topography of Lake Neusiedl. It must be stated, however, that (proto)dolomite formation is still incompletely understood (Neuhuber et al., 2024). Some clay minerals, such as smectites, might even facilitate protodolomite formation (Molnár et al., 2021). If the conditions in soda pans are comparable to Lake Neusiedl, these findings indicate that a water column is necessary or at least facilitates protodolomite formation in soda pans. Examined,

relatively intact, soda pans, such as Illmitzer Zicksee and Martenhoflacke, both exhibited topsoil pH ($\approx 8.6 - 9.0$) that seemed suitable for ongoing protodolomite formation. Comparing topsoil IC% and clay mineralogy in Martenhoflacke and Illmitzer Zicksee reveals that recent carbonate precipitation/protodolomite formation seemingly occurs more readily in the latter, further supporting the hypothesis of increased precipitation through free water tables and, potentially, smectite content. This finding is further supported by very low PC2_{up} values in Martenhoflacke, whereby PC2_{up} might connect to (proto)dolomite formation due to its strong positive correlation with exchangeable Mg²⁺ and inorganic carbon levels. Following this argumentation, since PC2_{up} was comparable to Illmitzer Zicksee, for Moschadolacke, protodolomite formation might have occurred in the past as well, indicating longer-lasting free water tables. Even though the lakebed of Moschadolacke is very shallow, due to its lower absolute topography, higher contributions of groundwater to free water tables than in Martenhoflacke might be possible.

In the subsoil, IC% were among the highest in Martenhoflacke, indicating carbonate enrichment or the deposition of substrates with higher carbonate contents at this depth. Exchangeable Mg²⁺ reached the lowest values in Martenhoflacke as well. From a clay mineralogical perspective, peak heights of protodolomite were higher than in the topsoil, albeit relatively low, when compared to the other two lakes. These findings indicate that carbonate enrichment in the subsoil occurred in Martenhoflacke as well, however past/present protodolomite formation was/is still lower than in both other soda pans.

4.4.2. Groundwater levels and SHC

The hypothesis of isolated groundwater bodies in soda pans has two potential consequences for SHC: (1) the hydraulic potential is different if groundwater table depths vary across soda pans, and (2) varying groundwater table depths might influence saline soil development.

To support his theory, Häusler, 2023 measured groundwater levels around Illmitzer Zicksee and indeed found groundwater table differences of >1 m ($-1,1$ m/ $-2,3$ m) in the area of Zi3, while in the central area of Illmitzer Zicksee (app. Zi1), no groundwater was found until a depth of -2.8 m (Häusler, 2023, S. 65f). This indicates that no uniform upper groundwater layer and consequently uniform hydraulic potential according to elevation can be assumed for Illmitzer Zicksee. From the SHC measurements conducted in this study, it seems as if hydraulic potential was not a major factor in determining SHC because of the relatively low variability of k_f values across elevation levels. This further supports the notion that topsoil stability is the major factor in determining SHC within soda pans.

Nevertheless, groundwater levels are still important for SHC in soda pans because of the minimal depth (≈ 2 m) necessary to maintain capillary transport and accumulation of salts (Chang et al., 2025) and subsequent conservation of saline soils dispersivity. This holds true whether saline groundwater or a primary saline horizon is the main source of salt in the region, because the downward movement of salts through infiltrating rainwater must be balanced by capillary rise of salts. As was observed in downward water movement, capillary rise is also influenced by changing vertical layer texture and micropores (Zhao et al., 2023). Arguably, this would play an important role in soda pans because of their supposed fluvial origin. Another important difference across soda pans might be their smectite content and differences in shrinkage crack formation. Varela et al., 2024 noted that capillary barriers might arise from horizontal shrinkage cracks, which would theoretically occur mostly in soils containing smectite. It remains an open question to what extent these factors influence necessary groundwater table depths. Furthermore, it seems unclear to what extent the transport of salt within soda pans through wind (another potential explanation of high $\text{Na}(\text{H}_2\text{O})$ at Ma5) or free water tables (an explanation for the uniform distribution of saline soils in Illmitzer Zicksee) facilitates the persistence of saline soils across a soda pan.

4.5. Conclusion

As stated in hypothesis H1.1, SHC varied, at least to some degree, across all soda pans and measurement sites, whereby Martenhoflacke yielded the lowest SHC on average ($k_f 10^\circ\text{C corr} = -8.04 \pm 1.4 \text{ m/s}$) followed by Illmitzer Zicksee ($k_f 10^\circ\text{C corr} = -7.69 \pm 0.42 \text{ m/s}$). From a statistical perspective, both lakes were equal and could be differentiated from Moschadolacke ($k_f 10^\circ\text{C corr} = -6.73 \pm 1.05 \text{ m/s}$). Nevertheless, when comparing results for central, saline soil areas of Martenhoflacke with similar areas in Illmitzer Zicksee, SHC was consistently lower in Martenhoflacke. Consequently, hypothesis H1.1 can be partly confirmed, especially when considering degraded (Moschadolacke) and “functional” soda pans (Martenhoflacke and Illmitzer Zicksee) and saline soils in different soda pans.

From the findings of this study, hypothesis H1.2 can be partly verified, because topsoil dispersivity and high pH through soluble and exchangeable Na^+ arguably were key processes in reducing SHC. This claim is supported by strong negative correlations of SHC with topsoil pH ($R^2 = 0.551$, $p < 0.05$) and PC1_{up} ($R^2 = 0.61$, $p < 0.05$), a factor mostly representing topsoil dispersivity. Furthermore, SHC was strongly positively correlated with soluble Ca^{2+} (e.g. $\text{Ca}(\text{H}_2\text{O})$: $R^2 = 0.62$, $p < 0.05$) indicating that flocculation was an important process in increasing SHC and lower pH improved the availability of soluble Ca^{2+} . The hypothesis can not be fully confirmed, however, because topsoil OC% showed the strongest overall correlation and the strongest positive correlation with SHC ($R^2 = 0.775$, $p < 0.05$). Nonetheless, it is likely that OC% was, to some degree, influenced by soil ion content because high pH arguably facilitates low OC%. As shown in this study, plant-covered areas, on average, showed higher SHC ($k_f 10^\circ\text{C corr} = -6.56 \pm 0.80$) than unvegetated areas ($k_f 10^\circ\text{C corr} = -8.41 \pm 0.73$). Further examinations are necessary to determine whether plant cover increased over the last decades and how this process is connected with soil property changes. Other variables, such as soil texture and particularly clay content were only weakly correlated with SHC (e.g. clay%: $R^2 = 0.25$, $p < 0.05$). The relatively weak influence of soil texture on SHC could also be confirmed by comparing literature values for certain soil textures with lower SHC obtained on saline soils in Martenhoflacke. Differences in SHC between saline soil sites on Martenhoflacke and Illmitzer Zicksee might stem from clay mineralogy, which influences soil dispersivity and soil swelling/shrinking behavior. Therefore, from the findings of this study, smectite and protodolomite content, particularly in the topsoil, might have had different effects on SHC in saline soils than prominently assumed: SHC in a smectite containing soil at Illmitzer Zicksee was indeed higher than in Martenhoflacke. Furthermore, although protodolomite was found in the clay fraction of both lakes, a sealing effect of this potentially authigenically formed material could not be proven since topsoil clay% only showed low negative correlations with SHC. Furthermore, SHC was lowest in Martenhoflacke, a soda pan which showed low contents of protodolomite and relatively low IC% in the topsoil.

Consequently, in-depth studies on clay mineralogy in soda pans are required to determine the distribution of smectites within soda pans and to determine whether the possible, authigenic formation of both smectite and protodolomite occurs at least within some soda pans. This might not only improve the prediction of SHC, but also shed light on the formation, as well as past and present conditions (pH, free water tables) of

saline soils and soda pans. Lastly, from the results of this study, it became apparent that subsoil properties were not relevant for measured SHC, underlining the importance of topsoils for SHC in soda pans.

Hypothesis H1.3 of lower SHC and subsequent longer times under water saturation could not be confirmed within this study. Instead, Illmitzer Zicksee, which showed higher saline soil SHC than Martenhoflacke, maintained a free water table during SHC measurements in August while Martenhoflacke dried out. Within this work, the shape of the lakebed and subsequent evaporation have been determined as drivers for this observation. This is caused (1) by the size of the catchment area which usually consists only of the lakebed and (2) by the form of the lakebed, whereby lakebeds that are deeper might have a better retention capacity than shallow lakebeds, because evaporation increases through higher surface areas of the resulting water table. Lower SHC in the catchment area, however, remains important to improve water collection in the lakebed. From these findings, it can be concluded that some soda pans naturally might not exhibit long-lasting water saturation regardless of low SHC (Martenhoflacke), while others maintain water saturation for extended time periods through larger catchment areas and deeper lakebeds (Illmitzer Zicksee). Nevertheless, in degraded soda pans, such as Moschadolacke, high SHC throughout the catchment area impedes water collection. In this context, future warming scenarios and consequent evaporation increases through climate change must indeed be considered in Austrian soda pan development.

Lastly, hypothesis H1.4 could be confirmed for Martenhoflacke and partly confirmed for Moschadolacke. However, the hypothesis could not be confirmed for Illmitzer Zicksee. In this study, no groundwater could be determined for depths >1m on all measurement sites. From existing examinations of groundwater at Illmitzer Zicksee, it is known that groundwater table depth varies greatly within this lake, possibly due to small, isolated groundwater bodies. However, Illmitzer Zicksee exhibited saline soils and unvegetated areas on almost the entire transect and elevations ($\Delta_{\text{elevation}} = 68 \text{ cm}$). This study could therefore not quantify the importance of groundwater tables and/or free water tables in the persistence of saline soils within this soda pan. On the other hand, in Martenhoflacke, saline soils and low SHC areas were located on a mostly flat central area, while elevated measurement sites exhibited non-saline soils and were plant-covered. In Moschadolacke, it seems likely that human activities led to lower SHC in the center through excavation activities and topsoil removal which increased BD and removed the vegetation cover. Nonetheless, in central Moschadolacke, groundwater influence and subsequent salinization were unlikely, considering similar elevation levels along the whole transect and highly increased SHC on other measurement sites in the transect. Furthermore, soil soluble and exchangeable Na^+ content indicated a dominance of top-down water movement instead of capillary rise.

5. References

- Abascal, J. L. F. and Vega, C. (2005) 'A general purpose model for the condensed phases of water: TIP4P/2005', *The Journal of Chemical Physics*, vol. 123, no. 23, pp. 1–12.
- Adams, W. A. (1973) 'The effect of organic matter on the bulk and true densities of some uncultivated Podzolic Soils', *Journal of Soil Science*, vol. 24, no. 1, pp. 10–17.
- Al Omari, M. M. H., Rashid, I. S., Qinna, N. A., Jaber, A. M. and Badwan, A. A. (2016) 'Calcium Carbonate', *Profiles of drug substances, excipients, and related methodology*, vol. 41, pp. 31–132.
- Arora, H. S. and Coleman, N. T. (1979) 'The influence of electrolyte concentration on flocculation of clay suspensions', *Soil Science*, vol. 127, no. 3, p. 134.
- Assouline, S. (2006) 'Modeling the Relationship between Soil Bulk Density and the Hydraulic Conductivity Function', *Vadose Zone Journal*, vol. 5, no. 2, pp. 697–705.
- Bagarello, V., Iovino, M., Palazzolo, E., Panno, M. and Reynolds, W. D. (2006) 'Field and laboratory approaches for determining sodicity effects on saturated soil hydraulic conductivity', *Geoderma*, vol. 130, 1-2, pp. 1–13.
- Baranyi, S., Boroviczeny, F., Deak, J., Dreher, J., Liebe, P., Mahler, H., Major, P., Neppel, F., Rajner, V., Rank, D. and Reitingner, J. (1986) 'Wasserhaushaltsstudie für den Neusiedlersee mit Hilfe der Geochemie und Geophysik. Rückblick auf den 1. Projektabschnitt 1980 bis 1984. Vorschau auf den 2. Projektabschnitt 1985 bis 1989.' , BFB-Bericht, no. 58, pp. 85–91.
- Bargués-Tobella, A., Winowiecki, L. A., Sheil, D. and Vågen, T.-G. (2024) 'Determinants of Field-Saturated Soil Hydraulic Conductivity Across Sub-Saharan Africa: Texture and Beyond', *Water Resources Research*, vol. 60, no. 1.
- Beck-Broichsitter, S., Rizvi, Z. H., Horn, R. and Wuttke, F. (2023) 'Effect of gravel content on soil water retention characteristics and thermal capacity of sandy and silty soils', *Journal of Hydrology and Hydromechanics*, vol. 71, no. 1, pp. 1–10.
- Bell, S. M., Terrer, C., Barriocanal, C., Jackson, R. B. and Rosell-Melé, A. (2021) 'Soil organic carbon accumulation rates on Mediterranean abandoned agricultural lands', *The Science of the total environment*, vol. 759, pp. 1–13.
- Belocky, R., Hübl, G., Papesch, W., Rank, D. and Römer, A. (1998) *Hydrologie und Hydrogeologie des Gebietes Lange Lacke - Wörtenlacken unter besonderer Berücksichtigung der Wechselwirkung zwischen Lacken- und Grundwasser*, Österreichisches Forschungs- und Prüfzentrum Arsenal Ges.m.b.H.
- Benjamin, J. G., Mikha, M. M. and Vigil, M. F. (2008) 'Organic Carbon Effects on Soil Physical and Hydraulic Properties in a Semiarid Climate', *Soil Science Society of America Journal*, vol. 72, no. 5, pp. 1357–1362.
- Bernhauser, A. (1977) 'Probleme der Geologie des burgenländischen Seewinkels', *Mitteilungen der österreichischen bodenkundlichen Gesellschaft*, 18-19, pp. 48–54.

- Blume, H.-P., Brümmer, G. W., Horn, R., Kandeler, E., Kögel-Knabner, I., Kretzschmar, R., Stahr, K. and Wilke, B.-M. (2010) Scheffer/Schachtschabel: Lehrbuch der Bodenkunde, Berlin, Heidelberg, Springer Berlin Heidelberg.
- Boros, E., Ecsedi, Z. and Olah, J. (eds) (2013) Ecology and management of soda pans in the Carpathian basin, Balmazújvaros, Hortobagy Environmental Association.
- Bristow, T. F., Kennedy, M. J., Morrison, K. D. and Mrofka, D. D. (2012) 'The influence of authigenic clay formation on the mineralogy and stable isotopic record of lacustrine carbonates', *Geochimica et Cosmochimica Acta*, vol. 90, pp. 64–82.
- Cai, W., Bordoloi, S., Zhu, C. and Gupt, C. B. (2023) 'Influence of plasticity and pore water salinity on shrinkage and water retention characteristics of biochar-engineered clays', *Soil Science Society of America Journal*, vol. 87, no. 6, pp. 1285–1303.
- Chang, C., Yang, G., Li, S., Wang, H. and Song, Y. (2025) 'Spatial characteristics and critical groundwater depth of soil salinization in arid artesian irrigation area of northw est China', *Agricultural Water Management*, vol. 307, pp. 1–11.
- Csaplovics, A., Götzinger, M. A. and Lengauer, C. L. (2018) 'Die Salzminerale der Salzlacken im Seewinkel, Burgenland', *Mitteilungen der österreichischen geologische n Gesellschaft*, vol. 164, pp. 55–64.
- Deer, W. A., FRS, Howie, R. A. and Zussman, J. (2013) An Introduction to the Rock-Forming Minerals, Mineralogical Society of Great Britain and Ireland.
- Draganits, E., Weißl, M., Zámolyi, A. and Doneus, M. (2022) 'Lake Neusiedl Area: A Particular Lakescape at the Boundary Between Alps and Pannonian Basin', in Embleton-Hamann, C. (ed) *Landscapes and Landforms of Austria*, Cham, Springer International Publishing, pp. 207–222.
- Dreher, J., Rajner, V., Rank, D. and Reiting, J. (1986) 'Grundwasseruntersuchungen am Ostufer des Neusiedlersees und im Seewinkel. Ergebnisse und Schlussfolgerungen.', *BFB-Bericht*, no. 58, pp. 39–50.
- Eitzinger, J., Kubu, G., Formayer, H., Haas, P., Gerersdorfer, T., Kromp-Kolb and H. (2009) Auswirkungen einer Klimaänderung auf den Wasserhaushalt des Neusiedlersees: Endbericht im Auftrag der Burgenländischen Landesregierung vom 15. Juli 2005, Universität für Bodenkultur.
- Elhassan, A. A., Mnzool, M., Smaoui, H., Jendoubi, A., Elnaim, B. M. and Faihan Alotaibi, M. (2023) 'Effect of clay mineral content on soil strength parameters', *Alexandria Engineering Journal*, vol. 63, pp. 475–485.
- European Council (2013) Council Directive 2013/17/EU (Document 32013L0017).
- Fang, M., Yu, H. and Hutson, A. (2024) CRAN: Contributed Packages.
- Franz, H. and Husz, G. (1961) 'Die Salzböden und das Alter der Salzsteppe im Seewinkel', *Mitteilungen der österreichischen bodenkundlichen Gesellschaft*, no. 6, pp. 67–75.
- Fritsch, V. and Tauber, A. F. (1959) 'Die Mineralwässer des Neusiedlerseegebietes', *Wissenschaftliche Arbeiten aus dem Burgenland*, vol. 23, pp. 34–39.

- Fuchs, W. (1974) 'Bericht über Exkursionen in die Oststeiermark, in das südliche Burgenland und nach Westungarn zur Klärung der Herkunft der Seewinkelschotter', Verhandlungen der Geologischen Bundesanstalt, pp. 118–121.
- Gao, M., Liang, F., an Yu, Li, B. and Yang, L. (2010) 'Evaluation of stability and maturity during forced-aeration composting of chicken manure and sawdust at different C/N ratios', Chemosphere, vol. 78, no. 5, pp. 614–619.
- Geosphere Austria (2020) SPARTACUS v2.1 Monatsdaten.
- Ghobadian, A. (1966) 'Salz- und Steppenböden des Seewinkels (Burgenland, Österreich); Charakteristik, Meliorationsergebnisse und bodenwirtschaftliche Aspekte', Mitteilungen der österreichischen bodenkundlichen Gesellschaft, no. 10, 1–57.
- Gritzmann, R. and Dober, G. (2014) Hydrogeologische, sedimentologische und tonmineralogische Untersuchungen im Gebiet des Neusiedler Sees, Wien.
- GRUPPE WASSER (2021) Machbarkeitsstudie zur Erstellung eines Wasserbewirtschaftungsplans für das Projektgebiet Grenzraum Österreich (A) - Ungarn (H): Interner Bericht mit Seezuleitung, Hauptreferat Wasserwirtschaft.
- Gucker, C. L. (2008) *Phragmites australis* [Online], Rocky Mountain Research Station , U.S. Department of Agriculture. Available at <https://www.fs.usda.gov/database/feis/plants/graminoid/phraus/all.html#212> (Accessed 27 March 2025).
- Hailu, B. and Mehari, H. (2021) 'Impacts of Soil Salinity/Sodicity on Soil-Water Relations and Plant Growth in Dry Land Areas: A Review', Journal of Natural Sciences Research, vol. 12, no. 3, pp. 1–10.
- Häusler, H. (2007) Geologische Karte der Republik Österreich 1 : 50 000: Erläuterungen zu den Blättern 79 Neusiedl am See 80 Ungarisch-Altenburg 109 Pamhagen, Geologische Bundesanstalt.
- Häusler, H. (2020) 'Wie gelangte das Salz in die Salzlacken? – Zum Stand der Forschung über die Entstehung des „Salzführenden Horizontes“ und der Salzböden des Seewinkels', Acta ZooBot Austria, vol. 157, pp. 145–157.
- Häusler, H. (2023) 'On the hydrogeology of perched aquifers under saline pans of the Seewinkel (Northern Burgenland, Austria)', Berichte der GeoSphere Austria, vol. 145.
- Hernández, V. A. (2023) 'An overview of surface forces and the DLVO theory', ChemTexts, vol. 9, no. 4.
- Hölting, B. and Coldewey, W. G. (2019) Hydrogeologie: Einführung in die Allgemeine und Angewandte Hydrogeologie, 8th edn, Berlin, Heidelberg, Springer Berlin Heidelberg.
- Husz, G. (1961) 'Zur Bodenkartierung im Salzbodenberich des Seewinkels', Wissenschaftliche Arbeiten aus dem Burgenland, vol. 29, pp. 172–180.
- Husz, G. (1967) 'Ein Vergleich österreichischer und ungarischer Salz-Böden hinsichtlich ihres Chemismus und ihrer Textur', Wissenschaftliche Arbeiten aus dem Burgenland, no. 38, pp. 161–174.

IUSS Working Group WRB (2022) World Reference Base for Soil Resources: International soil classification system for naming soils and creating legends for soil maps.

Kabelka, D., Konvalina, P., Kopecký, M., Klenotová, E. and Šíma, J. (2025) 'Assessment of Soil Organic Matter and Its Microbial Role in Selected Locations in the South Bohemia Region (Czech Republic)', *Land*, vol. 14, no. 1, p. 183.

Kirschner, A. (2007) 'Vergleichende Mikrobiologie ökologisch intakter und degradiert Lacken – Bakterien als Bioindikatoren', in Naturschutzbund Burgenland (ed) *Renaturierung ausgewählter Salzlacken des burgenländischen Seewinkels: Endbericht*, Eisenstadt, pp. 44–51.

Korner, I. (2007) 'Ergebnisse der Vegetationsökologischen Untersuchungen 2004 – 2007', in Naturschutzbund Burgenland (ed) *Renaturierung ausgewählter Salzlacken des burgenländischen Seewinkels: Endbericht*, Eisenstadt, pp. 52–85.

Krachler, R., Korner, I., Dvorak, M., Milazowszky N., Rabitsch, W., Werba, F., Zulka, P. and Kirschner, A. (2012) *Die Salzlacken des Seewinkels: Erhebung des aktuellen ökologischen Zustandes sowie Entwicklung individueller Lackenerhaltungskonzepte für die Salzlacken des Seewinkels (2008 – 2011)*.

Krachler, R. and Krachler, R. (2007) 'Ergebnisse der chemischen Untersuchungen 2004 – 2007', in Naturschutzbund Burgenland (ed) *Renaturierung ausgewählter Salzlacken des burgenländischen Seewinkels: Endbericht*, Eisenstadt, pp. 12–43.

Krachler, R., Krachler, R., Milleret, E. and Wesner, W. (2000) 'Limnochemische Untersuchungen zur aktuellen Situation der Salzlacken im burgenländischen Seewinkel', *Burgenländische Heimatblätter*, vol. 62 [Online]. Available at https://www.parks.at/npsn/pdf_public/2020/40634_20201123_104908_limnochemische_untersuchung_der_salzlacken_krachler_et_al_bgld_heimatbl_2000.pdf.

Kuśmierz, S., Skowrońska, M., Tkaczyk, P., Lipiński, W. and Mielniczuk, J. (2023) 'Soil Organic Carbon and Mineral Nitrogen Contents in Soils as Affected by Their pH, Texture and Fertilization', *Agronomy*, vol. 13, no. 1, pp. 1–13.

Kuzyakov, Y., Kretschmar, A. and Stahr, K. (1999) 'Contribution of *Lolium perenne* rhizodeposition to carbon turnover of pasture soil', *Plant and Soil*, vol. 213, no. 1, pp. 127–136.

Lal, R. (2020) 'Soil organic matter and water retention', *Agronomy Journal*, vol. 112, no. 5, pp. 3265–3277.

Levy, G. J., Goldstein, D. and Mamedov, A. I. (2005) 'Saturated Hydraulic Conductivity of Semiarid Soils: Combined Effects of Salinity, Sodicty, and Rate of Wetting', *Soil Science Society of America Journal*, vol. 69, no. 3, pp. 653–662.

Li, X., Chang, S. X. and Salifu, K. F. (2014) 'Soil texture and layering effects on water and salt dynamics in the presence of a water table: a review', *Environmental Reviews*, vol. 22, no. 1, pp. 41–50.

Manrique, L. A., Jones, C. A. and Dyke, P. T. (1991) 'Predicting Cation-Exchange Capacity from Soil Physical and Chemical Properties', *Soil Science Society of America Journal*, vol. 55, no. 3, pp. 787–794.

- Marchuk, A. (2013) Effect of cations on structural stability of salt-affected soils, Adelaide, The University of Adelaide.
- Marchuk, A. and Rengasamy, P. (2011) 'Clay behaviour in suspension is related to the ionicity of clay–cation bonds', *Applied Clay Science*, vol. 53, no. 4, pp. 754–759.
- Marchuk, A., Rengasamy, P., McNeill, A. and Kumar, A. (2012) 'Nature of the clay - cation bond affects soil structure as verified by X-ray computed tomography', *Soil Research*, vol. 50, no. 8, pp.1–7.
- Martel, Y. A., Kimpe, C. R. de and Laverdière, M. R. (1978) 'Cation-exchange Capacity of Clay-rich Soils in Relation to Organic Matter, Mineral Composition, and Surface Area', *Soil Science Society of America Journal*, vol. 42, no. 5, pp. 764–767.
- Melo, B. A. G. de, Motta, F. L. and Santana, M. H. A. (2016) 'Humic acids: Structural properties and multiple functionalities for novel technological developments', *Material science & engineering. C, Materials for biological applications*, vol. 62, pp. 967–974.
- Molnár, Z., Pekker, P., Dódon, I. and Pósfai, M. (2021) 'Clay minerals affect calcium (magnesium) carbonate precipitation and aging', *Earth and Planetary Science Letters*, vol. 567, pp. 1–11.
- Moore, D. M. and Reynolds, R. C. (1997) *X-Ray Diffraction and the Identification and Analysis of Clay Minerals*, 2nd edn, Cambridge, Cambridge University Press.
- Mortimer, C. E. and Müller, U. (2020) *Chemie: Das Basiswissen der Chemie*, 13th edn, Stuttgart, New York, Georg Thieme Verlag.
- National Center for Biotechnology Information (2025) PubChem Compound Summary for CID 516892, Sodium Bicarbonate. [Online]. Available at <https://pubchem.ncbi.nlm.nih.gov/compound/Sodium-Bicarbonate> (Accessed 31 May 2025).
- National Institute of Standards and Technology (2025) Thermophysical Properties of Fluid Systems [Online]. Available at <https://webbook.nist.gov/chemistry/fluid/> (Accessed 1 June 2025).
- Neina, D. (2019) 'The Role of Soil pH in Plant Nutrition and Soil Remediation', *Applied and Environmental Soil Science*, vol. 2019, pp. 1–9.
- Nelhiebel, P. (1977) 'Die Bodenverhältnisse des Seewinkels', *Mitteilungen der österreichischen bodenkundlichen Gesellschaft*, 18-19, 83–103.
- Nelhiebel, P. (2001) 'Exkursion K1 Die Böden des Naturraumes Neusiedler See (Burgenland)', *Mitteilungen der Deutschen Bodenkundlichen Gesellschaft*, vol. 94, pp. 77–91.
- Nestroy, O., Aust, G., Blum, W., Englisch, M., Hager, H., Herzberger, E., Kilian, W., Nelhiebel, P., Ortner, G., Pecina, E., Pehamberger, A., Schneider, W. and Wagner, J. (2011) *Systematische Gliederung der Böden Österreichs: Österreichische Bodensystematik 2000 in der revidierten Fassung von 2011*.

- Nestroy, O. and Kuttner, M. (2022) 'Zur Kenntnis der Böden der österreichischen Region östlich des Neusiedler Sees und südlich der Parndorfer Platte', BFB-Bericht, vol. 95, pp. 1–53.
- Neuhuber, S., Gier, S., Draganits, E., Steier, P., Bolka, M., Ottner, F., Spötl, C., Hippler, D. and Meister, P. (2024) 'Radiocarbon ages of microcrystalline authigenic carbonate in Lake Neusiedl (Austria) suggest millennial-scale growth of Mg-calcite and protodolomite', *Sedimentology*, vol. 71, no. 3, pp. 912–940.
- Nielsen, D. C. and Vigil, M. F. (2018) 'Soil Water Extraction for Several Dryland Crops', *Agronomy Journal*, vol. 110, no. 6, pp. 2447–2455.
- Österreichisches Normungsinstitut (2001) L 1086-1: Chemische Bodenuntersuchungen, Wien.
- Österreichisches Normungsinstitut (2002a) B 4422-2: Erd- und Grundbau - Untersuchung von Böden, Wien.
- Österreichisches Normungsinstitut (2002b) L 1061-1: Physikalische Bodenuntersuchungen - Bestimmung der Korngrößenverteilung des Mineralbodens, Wien.
- Österreichisches Normungsinstitut (2002c) L 1061-2: Physikalische Bodenuntersuchungen - Bestimmung der Korngrößenverteilung des Mineralbodens, Wien.
- Österreichisches Normungsinstitut (2004) L 1060: Bodenuntersuchungen, Wien.
- Österreichisches Normungsinstitut (2006) L 1083: Chemische Bodenuntersuchungen, Wien.
- Panagea, I. S., Berti, A., Čermak, P., Diels, J., Elsen, A., Kusá, H., Piccoli, I., Poesen, J., Stoate, C., Tits, M., Toth, Z. and Wyseure, G. (2021) 'Soil Water Retention as Affected by Management Induced Changes of Soil Organic Carbon: Analysis of Long-Term Experiments in Europe', *Land*, vol. 10, no. 12, pp. 1–15.
- Perrone, J. and Madramootoo, C. A. (1994) 'Characterizing bulk density and hydraulic conductivity changes in a potato cropped field', *Soil Technology*, vol. 7, no. 3, pp. 261–268.
- Quirk, J. P. and Schofield, R. K. (1955) 'The effect of electrolyte concentration on soil permeability', *Journal of Soil Science*, vol. 6, no. 2, pp. 163–178.
- Rank, D. (1986) 'Das neue Bild des Grundwasserhaushalts im Neusiedlersee-Gebiet: Ergebnisse von Isotopenuntersuchungen', *Wasser und Abwasser*, no. 30, pp. 293–323.
- Reddy, P. S., Mohanty, B. and Rao, B. H. (2020) 'Influence of Clay Content and Montmorillonite Content on Swelling Behavior of Expansive Soils', *International Journal of Geosynthetics and Ground Engineering*, vol. 6, no. 1.
- Riedl, H. (1965) 'Beiträge zur Morphogenese des Seewinkels.', *Wissenschaftliche Arbeiten aus dem Burgenland*, vol. 34, pp. 5–28.
- Ross, D. S. and Skyrberg, U. (2023) 'Cation exchange capacity and reactions', *Encyclopedia of Soils in the Environment*, Second Edition, no. 2, pp. 32–42.

- Rücknagel, J., Götze, P., Hofmann, B., Christen, O. and Marschall, K. (2013) 'The influence of soil gravel content on compaction behaviour and pre-compression stress', *Geoderma*, 209-210, pp. 226–232.
- Rutter, E. B., Ruiz Diaz, D. and Hargrave, L. M. (2022) 'Evaluation of Mehlich-3 for determination of cation exchange capacity in Kansas soils', *Soil Science Society of America Journal*, vol. 86, no. 1, pp. 146–156.
- Scherf, E. (1935) 'Geologische und morphologische Verhältnisse des Pleistozäns und Holozäns der Grossen Ungarischen Tiefebene und ihre Beziehungen zur Bodenbildung, insbesondere der Alkalibodenentstehung', *Jahresbericht der Königlichen Ungarischen geologischen Anstalt über die Jahre 1925-1928*, pp. 274–301.
- Shainberg, I. and Letey, J. (1984) 'Response of soils to sodic and saline conditions', *Hilgardia*, vol. 52, no. 2, pp. 1–57.
- Shainberg, I. and Oster, J. D. (1978) *Quality of Irrigation Water*, International Irrigation Information Center.
Available at <https://books.google.at/books?id=wddkQgAACAAJ>.
- Soja, G., Züger, J., Knoflacher, M., Kinner, P. and Soja, A.-M. (2013) 'Climate impacts on water balance of a shallow steppe lake in Eastern Austria (Lake Neusiedl)', *Journal of Hydrology*, vol. 480, pp. 115–124.
- Steiner, K. H. (2006) 'Hydrologie und Lackenwasserhaushalt im Seewinkel', in Wolfram, G., Oberleitner, I., Rabitsch, W., Sauberer, N., Mazzucco, K., Holzer, T., Fröhlich, W., Eder, E., Albert, R., Zülka, K. P. and Korner, I. (eds) *Salzlebensräume in Österreich*, Wien, Umweltbundesamt/Federal Environmental Agency, pp. 59–70.
- Sümegi, P. and Boros, E. (2013) 'Origin and development of soda pans in the Carpathian basin', in Boros, E., Ecsedi, Z. and Olah, J. (eds) *Ecology and management of soda pans in the Carpathian basin*, Balmaújvár, Hortobágy Environmental Association, pp. 23–33.
- Umweltbundesamt (2019) *Lebensraumtypen nach Anhang I der FFH-Richtlinie in Österreich* [Online], Wien.
Available at https://www.umweltbundesamt.at/fileadmin/site/themen/naturschutz/anhang_i_lebensraumtypen_oesterreich.pdf (Accessed 25 April 2024).
- Varela, J., Keilegavlen, E., Nordbotten, J. M. and Radu, F. A. (2024) 'A model for saturated–unsaturated flow with fractures acting as capillary barriers', *Vadose Zone Journal*, vol. 23, no. 4, pp. 1–17.
- Vereecken, H., Amelung, W., Bauke, S. L., Bogen, H., Brüggemann, N., Montzka, C., Vanderborght, J., Bechtold, M., Blöschl, G., Carminati, A., Javaux, M., Konings, A. G., Kusche, J., Neuweiler, I., Or, D., Steele-Dunne, S., Verhoef, A., Young, M. and Zhang, Y. (2022) 'Soil hydrology in the Earth system', *Nature Reviews Earth & Environment*, vol. 3, no. 9, pp. 573–587.
- Vives-Peris, V., Ollas, C. de, Gómez-Cadenas, A. and Pérez-Clemente, R. M. (2020) 'Root exudates: from plant to rhizosphere and beyond', *Plant cell reports*, vol. 39, no. 1, pp. 3–17.

- Waring, B. G., Smith, K. R., Grote, E. E., Howell, A., Reibold, R., Tucker, C. L. and Reed, S. C. (2021) 'Climatic Controls on Soil Carbon Accumulation and Loss in a Dryland Ecosystems', *Journal of Geophysical Research: Biogeosciences*, vol. 126, no. 12, pp. 1–13.
- Wilding, L. P. and Rutledge, E. M. (1966) 'Cation-Exchange Capacity as a Function of Organic Matter, Total Clay, and Various Clay Fractions in a Soil Toposequence', *Soil Science Society of America Journal*, vol. 30, no. 6, pp. 782–785.
- Wolfram, G., Oberleitner, I., Rabitsch, W., Sauberer, N., Mazzucco, K., Holzer, T., Fröhlich, W., Eder, E., Albert, R., Zulka, K. P. and Korner, I. (eds) (2006) *Salzlebensräume in Österreich*, Wien, Umweltbundesamt/Federal Environmental Agency.
- WWF (n.d.) *Die Rettung der Salzlebensräume: Rettungsversuche für stark gefährdete Seewinkel-Lacken* [Online]. Available at <https://www.wwf.at/artikel/die-rettung-der-salzlebensraeume/> (Accessed 4 January 2025).
- Xiao, L., Chen, S., Han, F., Wang, T., Li, Y., Li, W., Yuan, G. and Wu, J. (2025) 'Unveiling carbon dynamics in year-round waterlogged pond fields: insights into soil organic carbon accumulation and sustainable management', *Carbon Research*, vol. 4, no. 1, pp. 1–12.
- Xiong, P., Zhang, Z. and Peng, X. (2022) 'Root and root-derived biopore interactions in soils: A review', *Journal of Plant Nutrition and Soil Science*, vol. 185, no. 5, pp. 643–655.
- Yang, F., Li, G. X., Yang, Q. Y. and Luo, W. H. (2013) 'Effect of bulking agents on maturity and gaseous emissions during kitchen waste composting', *Chemosphere*, vol. 93, no. 7, pp. 1393–1399.
- Yang, L., Luo, P., Wen, L. and Li, D. (2016) 'Soil organic carbon accumulation during post-agricultural succession in a karst area, southwest China', *Scientific reports*, vol. 6, pp. 1–18.
- Zhao, Z., Luo, Z., Sun, H., Li, H., Liu, Q. and Liu, H. (2023) 'Capillary Rise in Layered Soils', *Applied Sciences*, vol. 13, no. 6, pp. 1–18.
- Zimmermann-Timm, H. and Teubner, K. (2021) 'Folgen der Grundwassersenkung am Beispiel des Neusiedlers See – Seewinkel (Burgenland, Österreich)', in Lozán, J. L., Breckle, S.-W., Graßl, H. and Kasang, D. (eds) *Warnsignal Klima: Boden & Landnutzung*, Hamburg, Wissenschaftliche Auswertungen in Kooperation mit GEO, pp. 142–149.
- Zünterl, A., Neuhuber, S., Kogelbauer, I., Ottner, F., Dietzel, M. and Hippler, D. (2015) 'Highresolution SEM study of authigenic high-Mg calcite and (proto-) dolomite of Lake Neusiedl (Austria).', *Mitteilungen der Österreichischen Mineralogischen Gesellschaft*, vol. 161, p. 135.

6. Appendix

6.1. Measurement sites – additional information

6.1.1. Geographical coordinates and heights

Appendix Table 1 shows MGI Austria GK East coordinates and the topographic height of measurement sites as height above adriatic sea.

Appendix Table 1: MGI Austria GK East coordinates and height above adriatic sea of all measurement sites.

Soda pan	Site	X	Y	Height above adriatic sea [m]	Relative height (lowest point) [m]
Martenhoflacke	1	39405.0005	290404.0004	117.16	0
	2	39355.6425	290433.2527	117.20	+ 0.04
	3	39307.5912	290454.5499	117.26	+ 0.1
	4	39288.7833	290463.6894	117.43	+ 0.27
	5	39269.9546	290475.9175	117.89	+ 0.73
Moschadolacke	1	39460.9120	289958.3133	116.74	0
	2	39446.4973	289933.5070	116.93	+ 0.19
	3	39424.9923	289905.2259	116.88	+ 0.14
	4	39398.9826	289874.5030	116.90	+ 0.16
	5	39365.8198	289849.5706	117.02	+ 0.28
Illmitzer Zicksee	1	33825.3888	292242.5645	115.93	0
	2	33753.5980	292223.9509	115.96	+ 0.03
	3	33669.4720	292198.4249	116.18	+ 0.25
	4	33548.8979	292163.7578	116.31	+ 0.38
	5	33515.6535	292151.2133	116.61	+ 0.68

6.1.2. Pictures of selected measurement sites

The following pictures Appendix 1 to Appendix 10 show selected measurement sites.



Appendix 1: Martenhoflacke, Ma2 a P_{uncov} site



Appendix 2: Martenhoflacke, Ma3 a P_{uncov} site



Appendix 3: Martenhoflacke, Ma5 a P_{cov} site



Appendix 4: Illmitzer Zicksee, Zi3 (towards Zi1 and Zi2) a P_{uncov} , recently water-saturated, site



Appendix 5: Illmitzer Zicksee, Zi4 a P_{uncov} site



Appendix 6: Illmitzer Zicksee, Zi5 a P_{cov} site



Appendix 7: Moschadolacke, Mo1 a P_{uncov} site



Appendix 8: Moschadolacke, Mo2 a P_{cov} site, fully covered with common reed



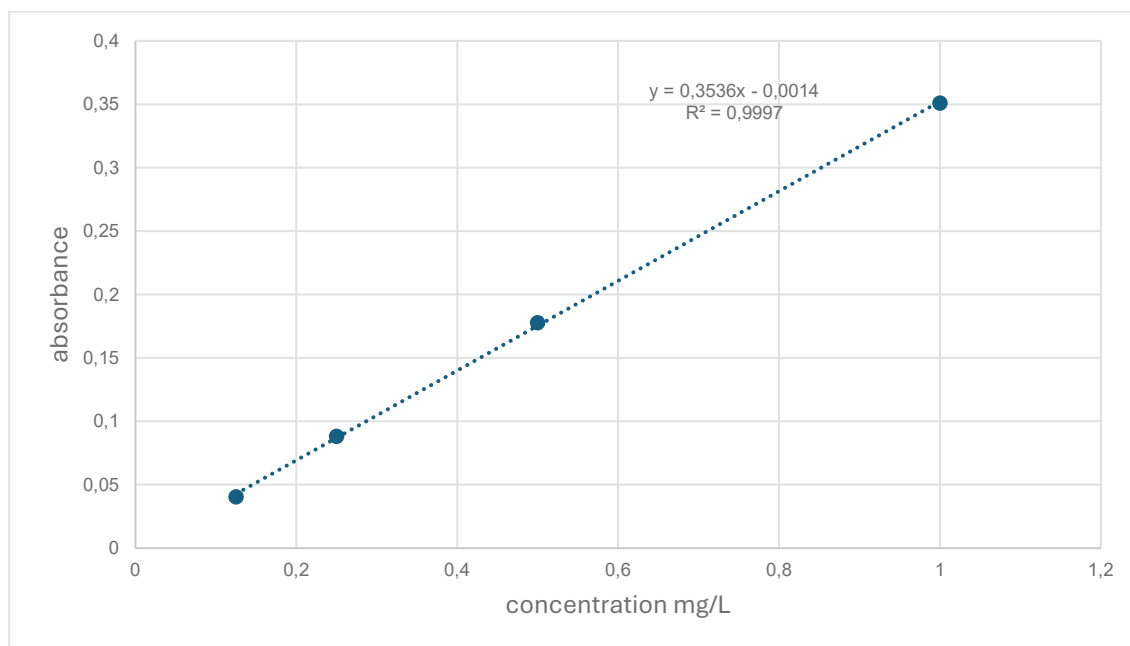
Appendix 9: Moschadolacke, Mo3 a P_{cov} site



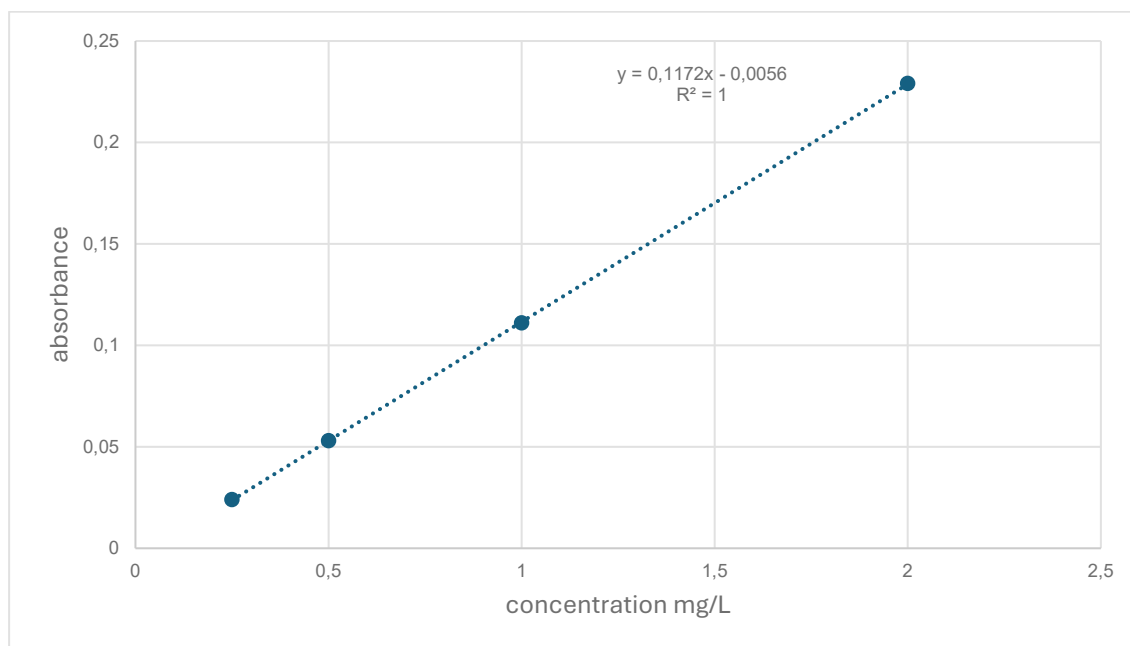
Appendix 10: Moschadolacke, Mo5 a P_{cov} site

6.2. Methods: Soil ion content – linear calibration slopes

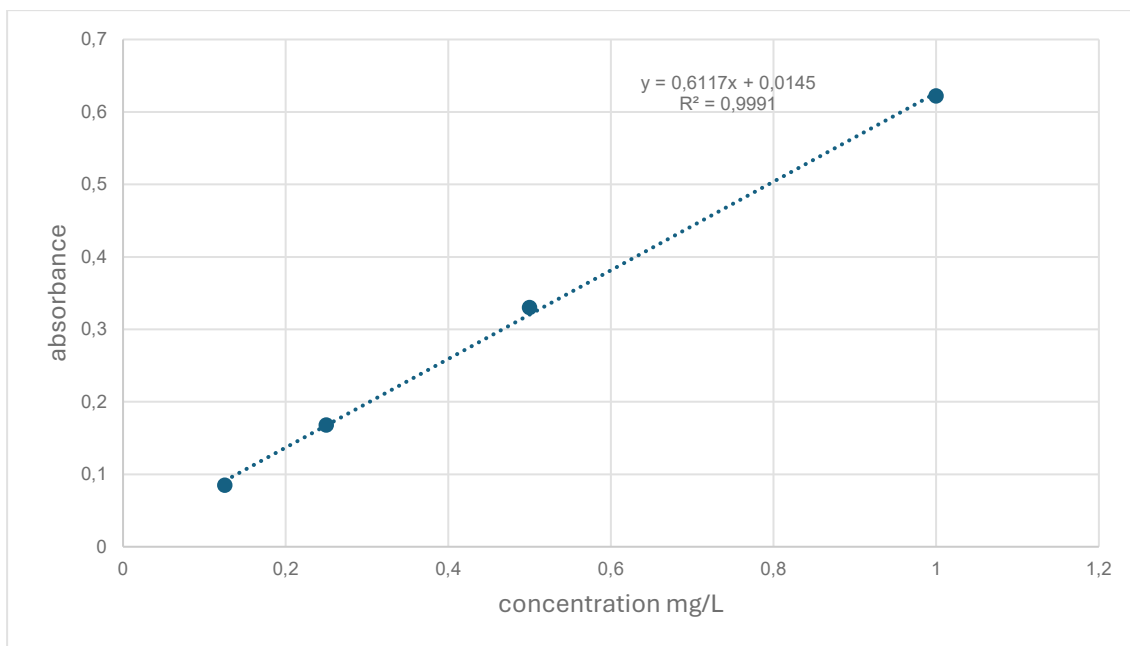
Appendix 11 to Appendix 14 show calibration slopes and R^2 values for all cation measurements.



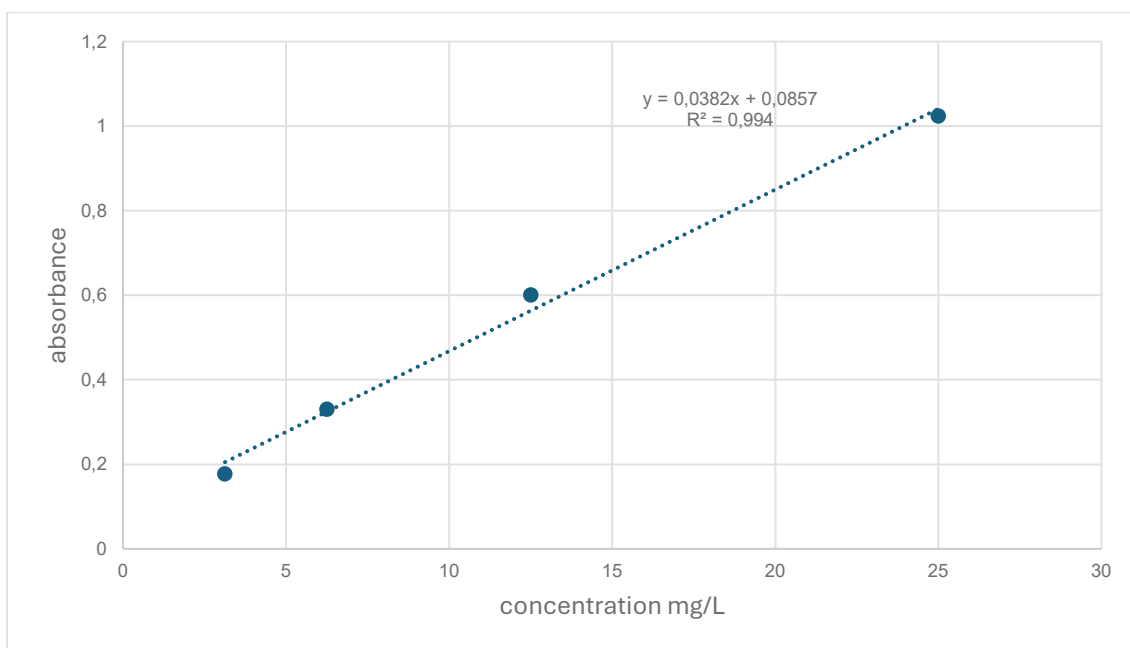
Appendix 11: linear calibration - Na⁺



Appendix 12: linear calibration - K⁺



Appendix 13: linear calibration - Mg^{2+}



Appendix 14: linear calibration- Ca^{2+}

6.3. Results: SHC measurements – raw data

In the following chapter SHC measurement results of each site are listed including supplementary variables. Appendix Table 2 acts as a translation table for measured variables, Appendix Table 3 lists measurement results.

Appendix Table 2: Variable numbers, names and description for k_f measurement results table Appendix Table 3

Variable number	Variable name	Description
[1]	date	Date of measurement
[2]	measurement ID	Site – infiltration experiment No – measurement No
[3]	T_{start} [°C]	Temperature of dest. water before start of infiltration
[4]	T_{end} [°C]	Temperature of dest. water after infiltration
[5]	T_{av} [°C]	Average temperature (T_{start} , T_{end})
[6]	t_{temp} [s]	Total time between temperature measurements
[7]	h_{start} [m]	Water height in the measurement pipette at the start of measurement
[8]	$h_{\text{end, uncorr}}$ [m]	Water height in the measurement pipette at the end of measurement; uncorr. – uncorrected for water volume increase
[9]	$t_{\text{infiltration}}$ [s]	Measurement time between h_{start} and $h_{\text{end, uncorr}}$
[10]	depth of infiltrometer [m]	Insertion depth of infiltrometer into soil
[11]	Δh_{start} [m]	Flow potential difference at h_{start}
[12]	$\Delta h_{\text{end, uncorr}}$ [m]	Uncorrected flow potential difference at $h_{\text{end, uncorr}}$
[13]	$h_{G, \text{start}}$ [m]	Flow potential at the start of measurement ($h_{\text{start}} + \Delta h_{\text{start}}$)
[14]	$h_{G, \text{end, uncorr}}$ [m]	Uncorrected flow potential at the end of measurement ($h_{\text{end, uncorr}} + \Delta h_{\text{end, uncorr}}$)
[15]	$k_{f, T_{\text{av, uncorr}}}$	Uncorrected k_f at T_{av}
[16]	$h_{V\text{change}}$ [m]	Calculated volume change measured in the measurement pipette during the infiltration period
[17]	$h_{\text{end, corr}}$ [m]	$h_{\text{end, uncorr}} + h_{V\text{change}}$ corr. – corrected for water volume increase
[18]	$\Delta h_{\text{end, corr}}$ [m]	Corrected flow potential difference at $h_{\text{end, corr}}$
[19]	$h_{G, \text{end, corr}}$ [m]	Corrected flow potential at the end of measurement ($h_{\text{end, corr}} + \Delta h_{\text{end, corr}}$)
[20]	$k_{f, T_{\text{av, corr}}}$ [m/s]	Corrected k_f at T_{av}
[21]	α	Factor for conversion of $k_{f, T_{\text{av, corr}}}$ to $k_{f, 10^\circ\text{C, corr}}$ (viscosity)
[22]	$k_{f, 10^\circ\text{C corr}}$ [m/s]	k_f at 10°C and corrected for volume change through temperature differences; negative values were changed to 10^{-10} for calculation purposes
[23]	measurement usage	Code: “empty cell” = unused measurement; Ma1 = (site), (1) = belongs to measurement series no. 1

[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]	[13]	[14]	[15]	[16]	[17]	[18]	[19]	[20]	[21]	[22]	[23]
10.08.2024	Ma1 - 1 - 1	27.0	26.6	26.8	3000	0.439	0.438	300	0.15	0.1375	0.1375	1.0915	1.0905	2.91E-09	-0.0003	0.438	0.1375	1.0905	2.91E-09	0.6622	1.93E-09	
10.08.2024	Ma1 - 1 - 2	27.0	26.6	26.8	3000	0.438	0.439	300	0.15	0.1375	0.1375	1.0905	1.0915	-2.91E-09	-0.0003	0.439	0.1375	1.0915	-2.91E-09	0.6622	-1.93E-09	
10.08.2024	Ma1 - 1 - 3	27.0	26.6	26.8	3000	0.439	0.439	300	0.15	0.1375	0.1375	1.0915	1.0915	0.00E+00	-0.0003	0.439	0.1375	1.0915	0.00E+00	0.6622	0.00E+00	Ma1 (1)
10.08.2024	Ma1 - 1 - 4	27.0	26.6	26.8	3000	0.439	0.439	300	0.15	0.1375	0.1375	1.0915	1.0915	0.00E+00	-0.0003	0.439	0.1375	1.0915	0.00E+00	0.6622	0.00E+00	Ma1 (1)
10.08.2024	Ma1 - 1 - 5	27.0	26.6	26.8	3000	0.439	0.439	300	0.15	0.1375	0.1375	1.0915	1.0915	0.00E+00	-0.0003	0.439	0.1375	1.0915	0.00E+00	0.6622	0.00E+00	Ma1 (1)
10.08.2024	Ma1 - 2 - 1	26.3	27.0	26.65	3900	0.444	0.444	300	0.157	0.1374	0.1374	1.0894	1.0894	0.00E+00	0.0004	0.444	0.1374	1.0894	0.00E+00	0.6644	0.00E+00	
10.08.2024	Ma1 - 2 - 2	26.3	27.0	26.65	3900	0.444	0.444	300	0.157	0.1374	0.1374	1.0894	1.0894	0.00E+00	0.0004	0.444	0.1374	1.0894	0.00E+00	0.6644	0.00E+00	
10.08.2024	Ma1 - 2 - 3	26.3	27.0	26.65	3900	0.444	0.444	300	0.157	0.1374	0.1374	1.0894	1.0894	0.00E+00	0.0004	0.444	0.1374	1.0894	0.00E+00	0.6644	0.00E+00	
10.08.2024	Ma1 - 2 - 4	26.3	27.0	26.65	3900	0.444	0.444	300	0.157	0.1374	0.1374	1.0894	1.0894	0.00E+00	0.0004	0.444	0.1374	1.0894	0.00E+00	0.6644	0.00E+00	
10.08.2024	Ma1 - 2 - 5	26.3	27.0	26.65	3900	0.444	0.444	300	0.157	0.1374	0.1374	1.0894	1.0894	0.00E+00	0.0004	0.444	0.1374	1.0894	0.00E+00	0.6644	0.00E+00	
15.08.2024	Ma1 - 3 - 1	29.6	32.0	30.8	4860	0.438	0.439	720	0.085	0.1421	0.1421	1.1601	1.1611	-1.14E-09	0.0037	0.435	0.1419	1.1569	3.42E-09	0.6076	2.08E-09	
15.08.2024	Ma1 - 3 - 2	29.6	32.0	30.8	4860	0.439	0.439	900	0.085	0.1421	0.1421	1.1611	1.1611	0.00E+00	0.0046	0.434	0.1418	1.1558	4.56E-09	0.6076	2.77E-09	
15.08.2024	Ma1 - 3 - 3	29.6	32.0	30.8	4860	0.439	0.44	420	0.085	0.1421	0.1422	1.1611	1.1622	-1.95E-09	0.0022	0.438	0.1421	1.1601	1.95E-09	0.6076	1.19E-09	Ma1 (2)
15.08.2024	Ma1 - 3 - 4	29.6	32.0	30.8	4860	0.44	0.442	720	0.085	0.1422	0.1423	1.1622	1.1643	-2.27E-09	0.0037	0.438	0.1421	1.1601	2.28E-09	0.6076	1.38E-09	Ma1 (2)
15.08.2024	Ma1 - 3 - 5	29.6	32.0	30.8	4860	0.442	0.442	720	0.085	0.1423	0.1423	1.1643	1.1643	0.00E+00	0.0037	0.438	0.1421	1.1601	4.55E-09	0.6076	2.76E-09	Ma1 (2)
13.08.2024	Ma2 - 1 - 1	33.4	32.1	32.75	2280	0.431	0.428	300	0.122	0.1390	0.1387	1.1130	1.1097	8.58E-09	-0.0017	0.430	0.1389	1.1119	2.86E-09	0.5836	1.67E-09	Ma2 (1)
13.08.2024	Ma2 - 1 - 2	33.4	32.1	32.75	2280	0.428	0.428	300	0.122	0.1387	0.1387	1.1097	1.1097	0.00E+00	-0.0017	0.430	0.1389	1.1119	-5.72E-09	0.5836	-3.34E-09	Ma2 (1)
13.08.2024	Ma2 - 1 - 3	33.4	32.1	32.75	2280	0.428	0.422	900	0.122	0.1387	0.1383	1.1097	1.1033	5.74E-09	-0.0052	0.427	0.1387	1.1087	9.55E-10	0.5836	5.57E-10	Ma2 (1)
14.08.2024	Ma2 - 2 - 1	35.2	35.5	35.35	3600	0.418	0.404	720	0.122	0.1380	0.1370	1.0990	1.0840	1.70E-08	0.0007	0.403	0.1369	1.0829	1.82E-08	0.5537	1.01E-08	
14.08.2024	Ma2 - 2 - 2	35.2	35.5	35.35	3600	0.404	0.396	720	0.122	0.1370	0.1364	1.0840	1.0754	9.82E-09	0.0007	0.395	0.1364	1.0744	1.11E-08	0.5537	6.12E-09	Ma2 (2)
14.08.2024	Ma2 - 2 - 3	35.2	35.5	35.35	3600	0.396	0.394	720	0.122	0.1364	0.1363	1.0754	1.0733	2.47E-09	0.0007	0.393	0.1362	1.0722	3.70E-09	0.5537	2.05E-09	Ma2 (2)
14.08.2024	Ma2 - 2 - 4	35.2	35.5	35.35	3600	0.394	0.392	720	0.122	0.1363	0.1362	1.0733	1.0712	2.47E-09	0.0007	0.391	0.1361	1.0701	3.71E-09	0.5537	2.05E-09	Ma2 (2)
14.08.2024	Ma2 - 2 - 5	35.2	35.5	35.35	3600	0.392	0.394	720	0.122	0.1362	0.1363	1.0712	1.0733	-2.47E-09	0.0007	0.393	0.1362	1.0722	-1.24E-09	0.5537	-6.85E-10	
15.08.2024	Ma2 - 3 - 1	32.1	32.6	32.35	4260	0.505	0.503	720	0.104	0.1454	0.1452	1.2114	1.2092	2.18E-09	0.0009	0.502	0.1452	1.2082	3.27E-09	0.5884	1.93E-09	Ma2 (3)
15.08.2024	Ma2 - 3 - 2	32.1	32.6	32.35	4260	0.503	0.502	720	0.104	0.1452	0.1452	1.2092	1.2082	1.09E-09	0.0009	0.501	0.1451	1.2071	2.19E-09	0.5884	1.29E-09	Ma2 (3)
15.08.2024	Ma2 - 3 - 3	32.1	32.6	32.35	4260	0.502	0.5	720	0.104	0.1452	0.1450	1.2082	1.2060	2.19E-09	0.0009	0.499	0.1450	1.2050	3.28E-09	0.5884	1.93E-09	Ma2 (3)
15.08.2024	Ma2 - 3 - 4	32.1	32.6	32.35	4260	0.5	0.499	720	0.104	0.1450	0.1450	1.2060	1.2050	1.10E-09	0.0009	0.498	0.1449	1.2039	2.19E-09	0.5884	1.29E-09	
15.08.2024	Ma2 - 3 - 5	32.1	32.6	32.35	4260	0.499	0.499	720	0.104	0.1450	0.1450	1.2050	1.2050	0.00E+00	0.0009	0.498	0.1449	1.2039	1.10E-09	0.5884	6.45E-10	
08.08.2024	Ma3 - 1 - 1	22.5	25.0	23.75	1800	0.447	0.443	300	0.118	0.1404	0.1401	1.1344	1.1301	1.12E-08	0.0032	0.440	0.1399	1.1269	1.97E-08	0.7091	1.39E-08	
08.08.2024	Ma3 - 1 - 2	22.5	25.0	23.75	1800	0.443	0.442	300	0.118	0.1401	0.1400	1.1301	1.1290	2.81E-09	0.0032	0.439	0.1398	1.1258	1.13E-08	0.7091	7.99E-09	
08.08.2024	Ma3 - 1 - 3	22.5	25.0	23.75	1800	0.442	0.441	300	0.118	0.1400	0.1400	1.1290	1.1280	2.81E-09	0.0032	0.438	0.1397	1.1247	1.13E-08	0.7091	7.99E-09	Ma3 (1)
08.08.2024	Ma3 - 1 - 4	22.5	25.0	23.75	1800	0.441	0.44	300	0.118	0.1400	0.1399	1.1280	1.1269	2.82E-09	0.0032	0.437	0.1397	1.1237	1.13E-08	0.7091	8.00E-09	Ma3 (1)
08.08.2024	Ma3 - 1 - 5	22.5	25.0	23.75	1800	0.44	0.439	300	0.118	0.1399	0.1398	1.1269	1.1258	2.82E-09	0.0032	0.436	0.1396	1.1226	1.13E-08	0.7091	8.01E-09	Ma3 (1)
21.08.2024	Ma3 - 2 - 1	24.2	27.9	26.05	2460	0.46	0.463	300	0.053	0.1458	0.1460	1.2178	1.2210	-7.79E-09	0.0043	0.459	0.1457	1.2167	2.60E-09	0.6732	1.75E-09	
21.08.2024	Ma3 - 2 - 2	24.2	27.9	26.05	2460	0.463	0.466	300	0.053	0.1460	0.1462	1.2210	1.2242	-7.77E-09	0.0043	0.462	0.1459	1.2199	2.60E-09	0.6732	1.75E-09	
21.08.2024	Ma3 - 2 - 3	24.2	27.9	26.05	2460	0.466	0.468	300	0.053	0.1462	0.1463	1.2242	1.2263	-5.17E-09	0.0043	0.464	0.1461	1.2221	5.18E-09	0.6732	3.49E-09	Ma3 (2)
21.08.2024	Ma3 - 2 - 4	24.2	27.9	26.05	2460	0.468	0.471	300	0.053	0.1463	0.1465	1.2263	1.2295	-7.74E-09	0.0043	0.467	0.1463	1.2253	2.58E-09	0.6732	1.74E-09	Ma3 (2)
21.08.2024	Ma3 - 2 - 5	24.2	27.9	26.05	2460	0.471	0.474	300	0.053	0.1465	0.1467	1.2295	1.2327	-7.72E-09	0.0043	0.470	0.1465	1.2285	2.58E-09	0.6732	1.73E-09	Ma3 (2)
21.08.2024	Ma3 - 3 - 1	24.1	28.6	26.35	3180	0.478	0.483	300	0.088	0.1446	0.1450	1.1996	1.2050	-1.32E-08	0.0038	0.479	0.1447	1.2007	-2.64E-09	0.6688	-1.77E-09	Ma3 (3)
21.08.2024	Ma3 - 3 - 2	24.1	28.6	26.35	3180	0.483	0.486	300	0.088	0.1450	0.1452	1.2050	1.2082	-7.88E-09	0.0038	0.482	0.1449	1.2039	2.63E-09	0.6688	1.76E-09	Ma3 (3)
21.08.2024	Ma3 - 3 - 3	24.1	28.6	26.35	3180	0.486	0.489	300	0.088	0.1452	0.1454	1.2082	1.2114	-7.86E-09	0.0038	0.485	0.1451	1.2071	2.62E-09	0.6688	1.75E-09	Ma3 (3)
21.08.2024	Ma3 - 3 - 4	24.1	28.6	26.35	3180	0.489	0.493	300	0.088	0.1454	0.1456	1.2114	1.2156	-1.04E-08	0.0038	0.489	0.1454	1.2114	0.00E+00	0.6688	0.00E+00	
21.08.2024	Ma3 - 3 - 5	24.1	28.6	26.35	3180	0.493	0.496	300	0.088	0.1456	0.1459	1.2156	1.2189	-7.81E-09	0.0038	0.492	0.1456	1.2146	2.61E-09	0.6688	1.74E-09	
09.08.2024	Ma4 - 1 - 1	27.5	30.5	29	1800	0.426	0.405	300	0.104	0.1399	0.1384	1.1269	1.1044	5.98E-08	0.0048	0.400	0.1380	1.0990	7.42E-08	0.6313	4.69E-08	Ma4 (1)
09.08.2024	Ma4 - 1 - 2	27.5	30.5	29	1800	0.405	0.396	120	0.104	0.1384	0.1377	1.1044	1.0947	6.50E-08	0.0019	0.394	0.1376	1.0926	7.96E-08	0.6313	5.02E-08	Ma4 (1)
09.08.2024	Ma4 - 1 - 3	27.5	30.5	29	1800	0.396	0.387	120	0.104	0.1377	0.1371	1.0947	1.0851	6.56E-08	0.0019	0.385	0.1369	1.0829	8.03E-08	0.6313	5.07E-08	Ma4 (1)
09.08.2024	Ma4 - 1 - 4	27.5	30.5	29	1800	0.387	0.38	120	0.104	0.1371	0.1366	1.0851	1.0776	5.15E-08	0.0019	0.378	0.1364	1.0754	6.62E-08	0.6313	4.18E-08	
09.08.2024	Ma4 - 1 - 5	27.5	30.5	29	1800	0.38	0.373	120	0.104	0.1366	0.1361	1.0776	1.0701	5.18E-08	0.0019	0.371	0.1359	1.0679	6.67E-08	0.6313	4.21E-08	
09.08.2024	Ma4 - 1 - 6	27.5	30.5	29	1800	0.373	0.354	240	0.104	0.1361	0.1347	1.0701	1.0497	7.1								

09.08.2024	Ma4 - 3 - 6	27.0	30.9	28.95	1800	0.218	0.097	240	0.116	0.1233	0.1132	0.8903	0.7592	5.91E-07	0.0048	0.092	0.1127	0.7537	6.17E-07	0.6320	3.90E-07	
09.08.2024	Ma5 - 1 - 1	32.3	32.9	32.6	1800	0.69	0.669	120	0.068	0.1597	0.1584	1.4467	1.4244	1.15E-07	0.0005	0.669	0.1584	1.4244	1.15E-07	0.5854	6.74E-08	Ma5 (1)
14.08.2024	Ma5 - 1 - 1	32.8	34.8	33.8	1320	0.4	0.3	57	0.077	0.1400	0.1327	1.1280	1.0207	1.56E-06	0.0010	0.299	0.1326	1.0196	1.58E-06	0.5712	9.00E-07	Ma5 (1)
09.08.2024	Ma5 - 1 - 2	32.3	32.9	32.6	1800	0.669	0.651	120	0.068	0.1584	0.1573	1.4244	1.4053	1.00E-07	0.0005	0.651	0.1573	1.4053	1.00E-07	0.5854	5.87E-08	Ma5 (1)
14.08.2024	Ma5 - 1 - 2	32.8	34.8	33.8	1320	0.4	0.3	58	0.077	0.1400	0.1327	1.1280	1.0207	1.53E-06	0.0010	0.299	0.1326	1.0196	1.55E-06	0.5712	8.85E-07	Ma5 (2)
09.08.2024	Ma5 - 1 - 3	32.3	32.9	32.6	1800	0.651	0.634	120	0.068	0.1573	0.1562	1.4053	1.3872	9.60E-08	0.0005	0.634	0.1562	1.3872	9.60E-08	0.5854	5.62E-08	Ma5 (2)
14.08.2024	Ma5 - 1 - 3	32.8	34.8	33.8	1320	0.4	0.3	58	0.077	0.1400	0.1327	1.1280	1.0207	1.53E-06	0.0010	0.299	0.1326	1.0196	1.55E-06	0.5712	8.85E-07	Ma5 (2)
09.08.2024	Ma5 - 1 - 4	32.3	32.9	32.6	1800	0.634	0.611	120	0.068	0.1562	0.1548	1.3872	1.3628	1.32E-07	0.0005	0.611	0.1548	1.3628	1.32E-07	0.5854	7.72E-08	
14.08.2024	Ma5 - 1 - 4	32.8	34.8	33.8	1320	0.4	0.3	60	0.077	0.1400	0.1327	1.1280	1.0207	1.48E-06	0.0010	0.299	0.1326	1.0196	1.50E-06	0.5712	8.55E-07	
09.08.2024	Ma5 - 1 - 5	32.3	32.9	32.6	1800	0.611	0.593	120	0.068	0.1548	0.1536	1.3628	1.3436	1.05E-07	0.0005	0.593	0.1536	1.3436	1.05E-07	0.5854	6.14E-08	
14.08.2024	Ma5 - 1 - 5	32.8	34.8	33.8	1320	0.4	0.3	59	0.077	0.1400	0.1327	1.1280	1.0207	1.51E-06	0.0010	0.299	0.1326	1.0196	1.52E-06	0.5712	8.70E-07	
14.08.2024	Ma5 - 2 - 1	29.1	28.2	28.65	1020	0.4	0.2	33	0.072	0.1403	0.1254	1.1333	0.9184	5.67E-06	-0.0003	0.200	0.1254	0.9184	5.67E-06	0.6360	3.61E-06	
14.08.2024	Ma5 - 2 - 2	29.1	28.2	28.65	1020	0.4	0.2	32	0.072	0.1403	0.1254	1.1333	0.9184	5.85E-06	-0.0003	0.200	0.1254	0.9184	5.85E-06	0.6360	3.72E-06	
14.08.2024	Ma5 - 2 - 3	29.1	28.2	28.65	1020	0.4	0.2	32	0.072	0.1403	0.1254	1.1333	0.9184	5.85E-06	-0.0003	0.200	0.1254	0.9184	5.85E-06	0.6360	3.72E-06	Ma5 (3)
14.08.2024	Ma5 - 2 - 4	29.1	28.2	28.65	1020	0.4	0.2	33	0.072	0.1403	0.1254	1.1333	0.9184	5.67E-06	-0.0003	0.200	0.1254	0.9184	5.67E-06	0.6360	3.61E-06	Ma5 (3)
14.08.2024	Ma5 - 2 - 5	29.1	28.2	28.65	1020	0.4	0.2	33	0.072	0.1403	0.1254	1.1333	0.9184	5.67E-06	-0.0003	0.200	0.1254	0.9184	5.67E-06	0.6360	3.61E-06	Ma5 (3)
14.08.2024	Mo1 - 1 - 1	36.9	37.0	36.95	3000	0.424	0.413	720	0.092	0.1406	0.1398	1.1376	1.1258	1.29E-08	0.0003	0.413	0.1398	1.1258	1.29E-08	0.5364	6.90E-09	
14.08.2024	Mo1 - 1 - 2	36.9	37.0	36.95	3000	0.413	0.404	720	0.092	0.1398	0.1392	1.1258	1.1162	1.06E-08	0.0003	0.404	0.1392	1.1162	1.06E-08	0.5364	5.70E-09	
14.08.2024	Mo1 - 1 - 3	36.9	37.0	36.95	3000	0.404	0.399	360	0.092	0.1392	0.1388	1.1162	1.1108	1.19E-08	0.0001	0.399	0.1388	1.1108	1.19E-08	0.5364	6.38E-09	Mo1 (1)
14.08.2024	Mo1 - 1 - 4	36.9	37.0	36.95	3000	0.399	0.395	360	0.092	0.1388	0.1385	1.1108	1.1065	9.55E-09	0.0001	0.395	0.1385	1.1065	9.55E-09	0.5364	5.13E-09	Mo1 (1)
14.08.2024	Mo1 - 1 - 5	36.9	37.0	36.95	3000	0.395	0.391	360	0.092	0.1385	0.1382	1.1065	1.1022	9.59E-09	0.0001	0.391	0.1382	1.1022	9.59E-09	0.5364	5.15E-09	Mo1 (1)
15.08.2024	Mo1 - 2 - 1	24.2	26.3	25.25	4320	0.459	0.456	720	0.076	0.1441	0.1439	1.1921	1.1889	3.33E-09	0.0031	0.453	0.1437	1.1857	6.67E-09	0.6854	4.57E-09	Mo1 (2)
15.08.2024	Mo1 - 2 - 2	24.2	26.3	25.25	4320	0.456	0.455	360	0.076	0.1439	0.1439	1.1889	1.1879	2.22E-09	0.0015	0.453	0.1437	1.1857	6.67E-09	0.6854	4.57E-09	Mo1 (2)
15.08.2024	Mo1 - 2 - 3	24.2	26.3	25.25	4320	0.455	0.453	360	0.076	0.1439	0.1437	1.1879	1.1857	4.45E-09	0.0015	0.451	0.1436	1.1836	8.91E-09	0.6854	6.11E-09	Mo1 (2)
15.08.2024	Mo1 - 2 - 4	24.2	26.3	25.25	4320	0.453	0.451	720	0.076	0.1437	0.1436	1.1857	1.1836	2.23E-09	0.0031	0.448	0.1434	1.1804	5.58E-09	0.6854	3.83E-09	
15.08.2024	Mo1 - 2 - 5	24.2	26.3	25.25	4320	0.451	0.449	720	0.076	0.1436	0.1435	1.1836	1.1815	2.23E-09	0.0031	0.446	0.1432	1.1782	5.59E-09	0.6854	3.83E-09	
21.08.2024	Mo1 - 3 - 1	21.4	23.1	22.25	1980	0.438	0.436	300	0.11	0.1403	0.1402	1.1333	1.1312	5.61E-09	0.0019	0.434	0.1400	1.1290	1.12E-08	0.7340	8.24E-09	
21.08.2024	Mo1 - 3 - 2	21.4	23.1	22.25	1980	0.436	0.436	300	0.11	0.1402	0.1402	1.1312	1.1312	0.00E+00	0.0019	0.434	0.1400	1.1290	5.62E-09	0.7340	4.13E-09	
21.08.2024	Mo1 - 3 - 3	21.4	23.1	22.25	1980	0.436	0.436	300	0.11	0.1402	0.1402	1.1312	1.1312	0.00E+00	0.0019	0.434	0.1400	1.1290	5.62E-09	0.7340	4.13E-09	Mo1 (3)
21.08.2024	Mo1 - 3 - 4	21.4	23.1	22.25	1980	0.436	0.437	300	0.11	0.1402	0.1402	1.1312	1.1322	-2.81E-09	0.0019	0.435	0.1401	1.1301	2.81E-09	0.7340	2.06E-09	Mo1 (3)
21.08.2024	Mo1 - 3 - 5	21.4	23.1	22.25	1980	0.437	0.438	300	0.11	0.1402	0.1403	1.1322	1.1333	-2.81E-09	0.0019	0.436	0.1402	1.1312	2.81E-09	0.7340	2.06E-09	Mo1 (3)
10.08.2024	Mo2 - 1 - 1	32.5	30.4	31.45	4740	0.4	0.3	23	0.095	0.1387	0.1313	1.1087	1.0013	3.94E-06	-0.0001	0.300	0.1313	1.0013	3.94E-06	0.5994	2.36E-06	Mo2 (1)
10.08.2024	Mo2 - 1 - 2	32.5	30.4	31.45	4740	0.4	0.3	23	0.095	0.1387	0.1313	1.1087	1.0013	3.94E-06	-0.0001	0.300	0.1313	1.0013	3.94E-06	0.5994	2.36E-06	Mo2 (1)
10.08.2024	Mo2 - 1 - 3	32.5	30.4	31.45	4740	0.4	0.3	23	0.095	0.1387	0.1313	1.1087	1.0013	3.94E-06	-0.0001	0.300	0.1313	1.0013	3.94E-06	0.5994	2.36E-06	Mo2 (1)
10.08.2024	Mo2 - 1 - 4	32.5	30.4	31.45	4740	0.4	0.3	24	0.095	0.1387	0.1313	1.1087	1.0013	3.78E-06	-0.0001	0.300	0.1313	1.0013	3.78E-06	0.5994	2.26E-06	
10.08.2024	Mo2 - 1 - 5	32.5	30.4	31.45	4740	0.4	0.3	25	0.095	0.1387	0.1313	1.1087	1.0013	3.62E-06	-0.0001	0.300	0.1313	1.0013	3.62E-06	0.5994	2.17E-06	
10.08.2024	Mo2 - 1 - 6	32.5	30.4	31.45	4740	0.4	0.3	24	0.095	0.1387	0.1313	1.1087	1.0013	3.78E-06	-0.0001	0.300	0.1313	1.0013	3.78E-06	0.5994	2.26E-06	
10.08.2024	Mo2 - 2 - 1	32.8	33.5	33.15	4740	0.4	0.3	11	0.048	0.1420	0.1348	1.1590	1.0518	7.85E-06	0.0000	0.300	0.1348	1.0518	7.85E-06	0.5788	4.54E-06	
10.08.2024	Mo2 - 2 - 2	32.8	33.5	33.15	4740	0.4	0.3	10	0.048	0.1420	0.1348	1.1590	1.0518	8.63E-06	0.0000	0.300	0.1348	1.0518	8.63E-06	0.5788	5.00E-06	
10.08.2024	Mo2 - 2 - 3	32.8	33.5	33.15	4740	0.4	0.3	11	0.048	0.1420	0.1348	1.1590	1.0518	7.85E-06	0.0000	0.300	0.1348	1.0518	7.85E-06	0.5788	4.54E-06	Mo2 (2)
10.08.2024	Mo2 - 2 - 4	32.8	33.5	33.15	4740	0.4	0.3	11	0.048	0.1420	0.1348	1.1590	1.0518	7.85E-06	0.0000	0.300	0.1348	1.0518	7.85E-06	0.5788	4.54E-06	Mo2 (2)
10.08.2024	Mo2 - 2 - 5	32.8	33.5	33.15	4740	0.4	0.3	11	0.048	0.1420	0.1348	1.1590	1.0518	7.85E-06	0.0000	0.300	0.1348	1.0518	7.85E-06	0.5788	4.54E-06	Mo2 (2)
10.08.2024	Mo2 - 3 - 1	31.3	29.0	30.15	4740	0.4	0.3	27	0.075	0.1401	0.1328	1.1301	1.0228	3.29E-06	-0.0001	0.300	0.1328	1.0228	3.29E-06	0.6160	2.02E-06	
10.08.2024	Mo2 - 3 - 2	31.3	29.0	30.15	4740	0.4	0.3	27	0.075	0.1401	0.1328	1.1301	1.0228	3.29E-06	-0.0001	0.300	0.1328	1.0228	3.29E-06	0.6160	2.02E-06	
10.08.2024	Mo2 - 3 - 3	31.3	29.0	30.15	4740	0.4	0.3	28	0.075	0.1401	0.1328	1.1301	1.0228	3.17E-06	-0.0001	0.300	0.1328	1.0228	3.17E-06	0.6160	1.95E-06	Mo2 (3)
10.08.2024	Mo2 - 3 - 4	31.3	29.0	30.15	4740	0.4	0.3	28	0.075	0.1401	0.1328	1.1301	1.0228	3.17E-06	-0.0001	0.300	0.1328	1.0228	3.17E-06	0.6160	1.95E-06	Mo2 (3)
10.08.2024	Mo2 - 3 - 5	31.3	29.0	30.15	4740	0.4	0.3	28	0.075	0.1401	0.1328	1.1301	1.0228	3.17E-06	-0.0001	0.300	0.1328	1.0228	3.17E-06	0.6160	1.95E-06	Mo2 (3)
12.08.2024	Mo3 - 1 - 1	36.6	37.1	36.85	960	0.4	0.3	36	0.108	0.1377	0.1303	1.0947	0.9873	2.55E-06	0.0002	0.300	0.1303	0.9873	2.55E-06	0.5375	1.37E-06	Mo3 (1)
12.08.2024	Mo3 - 1 - 2	36.6	37.1	36.85	960	0.4	0.3	37	0.108	0.1377	0.1303	1.0947	0.9873	2.48E-06	0.0002	0.300	0.1303	0.9873	2.48E-06	0.5375	1.33E-06	Mo3 (1)
12.08.2024	Mo3 - 1 - 3	36.6	37.1	36.85	960	0.4	0.3	36	0.108	0.1377	0.1303	1.0947	0.9873	2.55E-06	0.0002							

12.08.2024	Mo3 - 3 - 5	39.6	38.0	38.8	1020	0.4	0.38	27	0.076	0.1400	0.1386	1.1290	1.1076	6.31E-07	-0.0005	0.381	0.1387	1.1087	5.99E-07	0.5175	3.10E-07	
12.08.2024	Mo4 - 1 - 1	21.0	23.1	22.05	3240	0.49	0.456	300	0.096	0.1449	0.1426	1.2039	1.1676	9.09E-08	0.0014	0.455	0.1425	1.1665	9.36E-08	0.7375	6.90E-08	
12.08.2024	Mo4 - 1 - 2	21.0	23.1	22.05	3240	0.456	0.427	300	0.096	0.1426	0.1405	1.1676	1.1365	7.99E-08	0.0014	0.426	0.1405	1.1355	8.27E-08	0.7375	6.10E-08	
12.08.2024	Mo4 - 1 - 3	21.0	23.1	22.05	3240	0.4	0.38	235	0.096	0.1386	0.1372	1.1076	1.0862	7.40E-08	0.0011	0.379	0.1371	1.0851	7.77E-08	0.7375	5.73E-08	Mo4 (1)
12.08.2024	Mo4 - 1 - 4	21.0	23.1	22.05	3240	0.4	0.38	234	0.096	0.1386	0.1372	1.1076	1.0862	7.43E-08	0.0011	0.379	0.1371	1.0851	7.81E-08	0.7375	5.76E-08	Mo4 (1)
12.08.2024	Mo4 - 1 - 5	21.0	23.1	22.05	3240	0.4	0.38	236	0.096	0.1386	0.1372	1.1076	1.0862	7.37E-08	0.0011	0.379	0.1371	1.0851	7.74E-08	0.7375	5.71E-08	Mo4 (1)
12.08.2024	Mo4 - 2 - 1	20.8	25.7	23.25	5400	0.4	0.39	125	0.099	0.1384	0.1377	1.1044	1.0937	6.94E-08	0.0009	0.389	0.1376	1.0926	7.64E-08	0.7172	5.48E-08	
12.08.2024	Mo4 - 2 - 2	20.8	25.7	23.25	5400	0.4	0.39	147	0.099	0.1384	0.1377	1.1044	1.0937	5.90E-08	0.0010	0.389	0.1376	1.0926	6.50E-08	0.7172	4.66E-08	Mo4 (2)
12.08.2024	Mo4 - 2 - 3	20.8	25.7	23.25	5400	0.4	0.39	133	0.099	0.1384	0.1377	1.1044	1.0937	6.52E-08	0.0009	0.389	0.1376	1.0926	7.18E-08	0.7172	5.15E-08	Mo4 (2)
12.08.2024	Mo4 - 2 - 4	20.8	25.7	23.25	5400	0.4	0.39	135	0.099	0.1384	0.1377	1.1044	1.0937	6.43E-08	0.0010	0.389	0.1376	1.0926	7.07E-08	0.7172	5.07E-08	Mo4 (2)
12.08.2024	Mo4 - 2 - 5	20.8	25.7	23.25	5400	0.4	0.39	149	0.099	0.1384	0.1377	1.1044	1.0937	5.82E-08	0.0011	0.389	0.1376	1.0926	6.41E-08	0.7172	4.60E-08	
12.08.2024	Mo4 - 3 - 1	21.0	22.9	21.95	3460	0.4	0.3	139	0.078	0.1399	0.1326	1.1269	1.0196	6.40E-07	0.0006	0.299	0.1325	1.0185	6.47E-07	0.7392	4.78E-07	
12.08.2024	Mo4 - 3 - 2	21.0	22.9	21.95	3460	0.4	0.3	140	0.078	0.1399	0.1326	1.1269	1.0196	6.36E-07	0.0006	0.299	0.1325	1.0185	6.42E-07	0.7392	4.75E-07	
12.08.2024	Mo4 - 3 - 3	21.0	22.9	21.95	3460	0.4	0.3	143	0.078	0.1399	0.1326	1.1269	1.0196	6.22E-07	0.0006	0.299	0.1325	1.0185	6.29E-07	0.7392	4.65E-07	Mo4 (3)
12.08.2024	Mo4 - 3 - 4	21.0	22.9	21.95	3460	0.4	0.3	143	0.078	0.1399	0.1326	1.1269	1.0196	6.22E-07	0.0006	0.299	0.1325	1.0185	6.29E-07	0.7392	4.65E-07	Mo4 (3)
12.08.2024	Mo4 - 3 - 5	21.0	22.9	21.95	3460	0.4	0.3	144	0.078	0.1399	0.1326	1.1269	1.0196	6.18E-07	0.0006	0.299	0.1325	1.0185	6.25E-07	0.7392	4.62E-07	Mo4 (3)
13.08.2024	Mo5 - 1 - 1	27.6	29.4	28.5	1260	0.4	0.36	22	0.062	0.1410	0.1382	1.1440	1.1012	1.54E-06	0.0003	0.360	0.1382	1.1012	1.54E-06	0.6381	9.85E-07	
13.08.2024	Mo5 - 1 - 2	27.6	29.4	28.5	1260	0.4	0.36	24	0.062	0.1410	0.1382	1.1440	1.1012	1.41E-06	0.0003	0.360	0.1382	1.1012	1.41E-06	0.6381	9.03E-07	Mo5 (1)
13.08.2024	Mo5 - 1 - 3	27.6	29.4	28.5	1260	0.4	0.36	24	0.062	0.1410	0.1382	1.1440	1.1012	1.41E-06	0.0003	0.360	0.1382	1.1012	1.41E-06	0.6381	9.03E-07	Mo5 (1)
13.08.2024	Mo5 - 1 - 4	27.6	29.4	28.5	1260	0.4	0.36	25	0.062	0.1410	0.1382	1.1440	1.1012	1.36E-06	0.0004	0.360	0.1382	1.1012	1.36E-06	0.6381	8.67E-07	Mo5 (1)
13.08.2024	Mo5 - 1 - 5	27.6	29.4	28.5	1260	0.4	0.36	27	0.062	0.1410	0.1382	1.1440	1.1012	1.26E-06	0.0004	0.360	0.1382	1.1012	1.26E-06	0.6381	8.03E-07	
13.08.2024	Mo5 - 2 - 1	28.5	29.9	29.2	1740	0.4	0.36	85	0.062	0.1410	0.1382	1.1440	1.1012	3.99E-07	0.0007	0.359	0.1381	1.1001	4.10E-07	0.6286	2.58E-07	Mo5 (2)
13.08.2024	Mo5 - 2 - 2	28.5	29.9	29.2	1740	0.4	0.36	83	0.062	0.1410	0.1382	1.1440	1.1012	4.09E-07	0.0007	0.359	0.1381	1.1001	4.20E-07	0.6286	2.64E-07	Mo5 (2)
13.08.2024	Mo5 - 2 - 3	28.5	29.9	29.2	1740	0.4	0.36	77	0.062	0.1410	0.1382	1.1440	1.1012	4.41E-07	0.0006	0.359	0.1381	1.1001	4.52E-07	0.6286	2.84E-07	Mo5 (2)
13.08.2024	Mo5 - 2 - 4	28.5	29.9	29.2	1740	0.4	0.36	74	0.062	0.1410	0.1382	1.1440	1.1012	4.59E-07	0.0006	0.359	0.1381	1.1001	4.71E-07	0.6286	2.96E-07	
13.08.2024	Mo5 - 2 - 5	28.5	29.9	29.2	1740	0.4	0.36	75	0.062	0.1410	0.1382	1.1440	1.1012	4.53E-07	0.0006	0.359	0.1381	1.1001	4.64E-07	0.6286	2.92E-07	
13.08.2024	Mo5 - 3 - 1	31.5	31.4	31.45	1140	0.4	0.2	80	0.069	0.1405	0.1256	1.1365	0.9216	2.33E-06	-0.0001	0.200	0.1256	0.9216	2.33E-06	0.5994	1.40E-06	
13.08.2024	Mo5 - 3 - 2	31.5	31.4	31.45	1140	0.4	0.2	80	0.069	0.1405	0.1256	1.1365	0.9216	2.33E-06	-0.0001	0.200	0.1256	0.9216	2.33E-06	0.5994	1.40E-06	
13.08.2024	Mo5 - 3 - 3	31.5	31.4	31.45	1140	0.4	0.2	81	0.069	0.1405	0.1256	1.1365	0.9216	2.30E-06	-0.0001	0.200	0.1256	0.9216	2.30E-06	0.5994	1.38E-06	Mo5 (3)
13.08.2024	Mo5 - 3 - 4	31.5	31.4	31.45	1140	0.4	0.2	81	0.069	0.1405	0.1256	1.1365	0.9216	2.30E-06	-0.0001	0.200	0.1256	0.9216	2.30E-06	0.5994	1.38E-06	Mo5 (3)
13.08.2024	Mo5 - 3 - 5	31.5	31.4	31.45	1140	0.4	0.2	81	0.069	0.1405	0.1256	1.1365	0.9216	2.30E-06	-0.0001	0.200	0.1256	0.9216	2.30E-06	0.5994	1.38E-06	Mo5 (3)
17.08.2024	Zi1 - 1 - 1	33.2	33.7	33.45	1500	0.451	0.439	300	0.122	0.1404	0.1395	1.1344	1.1215	3.38E-08	0.0010	0.438	0.1395	1.1205	3.66E-08	0.5753	2.11E-08	
17.08.2024	Zi1 - 1 - 2	33.2	33.7	33.45	1500	0.439	0.433	300	0.122	0.1395	0.1391	1.1215	1.1151	1.70E-08	0.0010	0.432	0.1390	1.1140	1.99E-08	0.5753	1.14E-08	
17.08.2024	Zi1 - 1 - 3	33.2	33.7	33.45	1500	0.433	0.428	300	0.122	0.1391	0.1387	1.1151	1.1097	1.43E-08	0.0010	0.427	0.1387	1.1087	1.71E-08	0.5753	9.86E-09	Zi1 (1)
17.08.2024	Zi1 - 1 - 4	33.2	33.7	33.45	1500	0.428	0.423	300	0.122	0.1387	0.1384	1.1097	1.1044	1.44E-08	0.0010	0.422	0.1383	1.1033	1.72E-08	0.5753	9.91E-09	Zi1 (1)
17.08.2024	Zi1 - 1 - 5	33.2	33.7	33.45	1500	0.423	0.418	300	0.122	0.1384	0.1380	1.1044	1.0990	1.44E-08	0.0010	0.417	0.1380	1.0980	1.73E-08	0.5753	9.96E-09	Zi1 (1)
17.08.2024	Zi2 - 4 - 1	33.7	34.1	33.9	1080	0.393	0.383	300	0.102	0.1377	0.1369	1.0937	1.0829	2.92E-08	0.0012	0.382	0.1369	1.0819	3.22E-08	0.5700	1.83E-08	
17.08.2024	Zi2 - 4 - 2	33.7	34.1	33.9	1080	0.383	0.369	300	0.102	0.1369	0.1359	1.0829	1.0679	4.14E-08	0.0012	0.368	0.1359	1.0669	4.44E-08	0.5700	2.53E-08	
17.08.2024	Zi2 - 4 - 3	33.7	34.1	33.9	1080	0.369	0.365	120	0.102	0.1359	0.1356	1.0679	1.0636	2.99E-08	0.0005	0.365	0.1356	1.0636	2.99E-08	0.5700	1.70E-08	Zi2 (2)
17.08.2024	Zi2 - 4 - 4	33.7	34.1	33.9	1080	0.365	0.361	120	0.102	0.1356	0.1353	1.0636	1.0593	3.00E-08	0.0005	0.361	0.1353	1.0593	3.00E-08	0.5700	1.71E-08	Zi2 (2)
17.08.2024	Zi2 - 4 - 5	33.7	34.1	33.9	1080	0.361	0.3565	120	0.102	0.1353	0.1350	1.0593	1.0545	3.39E-08	0.0005	0.356	0.1350	1.0540	3.77E-08	0.5700	2.15E-08	Zi2 (2)
17.08.2024	Zi2 - 4 - 6	33.7	34.1	33.9	1080	0.3565	0.3525	120	0.102	0.1350	0.1347	1.0545	1.0502	3.03E-08	0.0005	0.352	0.1347	1.0497	3.40E-08	0.5700	1.94E-08	
17.08.2024	Zi3 - 1 - 1	23.8	25.0	24.4	2640	0.457	0.445	300	0.102	0.1422	0.1414	1.1622	1.1494	3.29E-08	0.0011	0.444	0.1413	1.1483	3.57E-08	0.6986	2.49E-08	
17.08.2024	Zi3 - 1 - 2	23.8	25.0	24.4	2640	0.445	0.432	300	0.102	0.1414	0.1405	1.1494	1.1355	3.61E-08	0.0011	0.431	0.1404	1.1344	3.89E-08	0.6986	2.72E-08	Zi3 (1)
17.08.2024	Zi3 - 1 - 3	23.8	25.0	24.4	2640	0.432	0.419	300	0.102	0.1405	0.1395	1.1355	1.1215	3.66E-08	0.0011	0.418	0.1395	1.1205	3.94E-08	0.6986	2.75E-08	Zi3 (1)
17.08.2024	Zi3 - 1 - 4	23.8	25.0	24.4	2640	0.419	0.407	300	0.102	0.1395	0.1387	1.1215	1.1087	3.42E-08	0.0011	0.406	0.1386	1.1076	3.71E-08	0.6986	2.59E-08	Zi3 (1)
17.08.2024	Zi3 - 1 - 5	23.8	25.0	24.4	2640	0.407	0.395	300	0.102	0.1387	0.1378	1.1087	1.0958	3.46E-08	0.0011	0.394	0.1377	1.0947	3.75E-08	0.6986	2.62E-08	
17.08.2024	Zi3 - 2 - 1	23.8	26.3	25.05	2520	0.466	0.455	300	0.102	0.1428	0.1421	1.1718	1.1601	2.99E-08	0.0025	0.453	0.1419	1.1579	3.54E-08	0.6885	2.44E-08	
17.08.2024	Zi3 - 2 - 2	23.8	26.3	25.05	2520	0.455	0.446	300	0.102	0.1421	0.1414	1.1601	1.1504	2.47E-08	0.0025	0.444	0.1413	1.1483	3.02E-08	0.6885	2.08E-08	
17.08.2024	Zi3 - 2 - 3	23.8	26.3	25.05	2520	0.446	0.437	300	0.102	0.1414	0.1408	1.1504	1.1408	2								

16.08.2024	Zi4 - 1 - 2	27.2	28.2	27.7	2760	0.463	0.447	300	0.114	0.1418	0.1407	1.1558	1.1387	4.43E-08	0.0010	0.446	0.1406	1.1376	4.71E-08	0.6493	3.06E-08	Zi4 (1)
16.08.2024	Zi4 - 1 - 3	27.2	28.2	27.7	2760	0.447	0.433	300	0.114	0.1407	0.1397	1.1387	1.1237	3.93E-08	0.0010	0.432	0.1396	1.1226	4.21E-08	0.6493	2.74E-08	Zi4 (1)
16.08.2024	Zi4 - 1 - 4	27.2	28.2	27.7	2760	0.433	0.408	540	0.114	0.1397	0.1379	1.1237	1.0969	3.98E-08	0.0018	0.406	0.1377	1.0947	4.30E-08	0.6493	2.79E-08	
16.08.2024	Zi4 - 1 - 5	27.2	28.2	27.7	2760	0.408	0.392	420	0.114	0.1379	0.1367	1.0969	1.0797	3.34E-08	0.0014	0.391	0.1367	1.0787	3.55E-08	0.6493	2.30E-08	
16.08.2024	Zi4 - 2 - 1	26.3	29.3	27.8	3420	0.438	0.433	300	0.075	0.1428	0.1424	1.1708	1.1654	1.36E-08	0.0026	0.430	0.1422	1.1622	2.18E-08	0.6478	1.41E-08	
16.08.2024	Zi4 - 2 - 2	26.3	29.3	27.8	3420	0.433	0.423	780	0.075	0.1424	0.1417	1.1654	1.1547	1.05E-08	0.0067	0.416	0.1412	1.1472	1.79E-08	0.6478	1.16E-08	Zi4 (2)
16.08.2024	Zi4 - 2 - 3	26.3	29.3	27.8	3420	0.423	0.42	300	0.075	0.1417	0.1415	1.1547	1.1515	8.26E-09	0.0026	0.417	0.1413	1.1483	1.65E-08	0.6478	1.07E-08	Zi4 (2)
16.08.2024	Zi4 - 2 - 4	26.3	29.3	27.8	3420	0.42	0.417	300	0.075	0.1415	0.1413	1.1515	1.1483	8.28E-09	0.0026	0.414	0.1411	1.1451	1.66E-08	0.6478	1.07E-08	Zi4 (2)
16.08.2024	Zi4 - 2 - 5	26.3	29.3	27.8	3420	0.417	0.414	360	0.075	0.1413	0.1411	1.1483	1.1451	6.92E-09	0.0031	0.411	0.1409	1.1419	1.39E-08	0.6478	8.98E-09	
16.08.2024	Zi4 - 2 - 6	26.3	29.3	27.8	3420	0.414	0.4115	300	0.075	0.1411	0.1409	1.1451	1.1424	6.94E-09	0.0026	0.409	0.1407	1.1397	1.39E-08	0.6478	9.00E-09	
16.08.2024	Zi4 - 3 - 1	27.8	28.9	28.35	2520	0.427	0.415	300	0.094	0.1407	0.1398	1.1387	1.1258	3.37E-08	0.0012	0.414	0.1397	1.1247	3.65E-08	0.6402	2.34E-08	
16.08.2024	Zi4 - 3 - 2	27.8	28.9	28.35	2520	0.415	0.405	300	0.094	0.1398	0.1391	1.1258	1.1151	2.84E-08	0.0012	0.404	0.1390	1.1140	3.12E-08	0.6402	2.00E-08	
16.08.2024	Zi4 - 3 - 3	27.8	28.9	28.35	2520	0.405	0.396	300	0.094	0.1391	0.1385	1.1151	1.1055	2.58E-08	0.0012	0.395	0.1384	1.1044	2.86E-08	0.6402	1.83E-08	Zi4 (3)
16.08.2024	Zi4 - 3 - 4	27.8	28.9	28.35	2520	0.396	0.387	300	0.094	0.1385	0.1378	1.1055	1.0958	2.60E-08	0.0012	0.386	0.1377	1.0947	2.89E-08	0.6402	1.85E-08	Zi4 (3)
16.08.2024	Zi4 - 3 - 5	27.8	28.9	28.35	2520	0.387	0.378	300	0.094	0.1378	0.1372	1.0958	1.0862	2.62E-08	0.0012	0.377	0.1371	1.0851	2.92E-08	0.6402	1.87E-08	Zi4 (3)
15.08.2024	Zi5 - 1 - 1	33.6	32.0	32.8	2880	0.466	0.444	300	0.087	0.1439	0.1423	1.1879	1.1643	5.93E-08	-0.0018	0.446	0.1425	1.1665	5.39E-08	0.5830	3.14E-08	
15.08.2024	Zi5 - 1 - 2	33.6	32.0	32.8	2880	0.444	0.432	300	0.087	0.1423	0.1415	1.1643	1.1515	3.29E-08	-0.0018	0.434	0.1416	1.1536	2.74E-08	0.5830	1.60E-08	Zi5 (1)
15.08.2024	Zi5 - 1 - 3	33.6	32.0	32.8	2880	0.429	0.416	300	0.087	0.1413	0.1404	1.1483	1.1344	3.62E-08	-0.0018	0.418	0.1405	1.1365	3.06E-08	0.5830	1.78E-08	Zi5 (1)
15.08.2024	Zi5 - 1 - 4	33.6	32.0	32.8	2880	0.416	0.403	300	0.087	0.1404	0.1395	1.1344	1.1205	3.66E-08	-0.0018	0.405	0.1396	1.1226	3.10E-08	0.5830	1.80E-08	Zi5 (1)
15.08.2024	Zi5 - 1 - 5	33.6	32.0	32.8	2880	0.403	0.393	300	0.087	0.1395	0.1387	1.1205	1.1097	2.85E-08	-0.0018	0.395	0.1389	1.1119	2.28E-08	0.5830	1.33E-08	
15.08.2024	Zi5 - 1 - 6	33.6	32.0	32.8	2880	0.393	0.381	300	0.087	0.1387	0.1379	1.1097	1.0969	3.46E-08	-0.0018	0.383	0.1380	1.0990	2.88E-08	0.5830	1.68E-08	
16.08.2024	Zi5 - 1 - 7	33.6	32.0	32.8	2880	0.381	0.369	300	0.087	0.1379	0.1370	1.0969	1.0840	3.50E-08	-0.0018	0.371	0.1372	1.0862	2.91E-08	0.5830	1.70E-08	
15.08.2024	Zi5 - 2 - 1	32.3	30.2	31.25	3000	0.423	0.415	300	0.078	0.1415	0.1409	1.1515	1.1429	2.21E-08	-0.0023	0.417	0.1411	1.1451	1.66E-08	0.6020	9.98E-09	
15.08.2024	Zi5 - 2 - 2	32.3	30.2	31.25	3000	0.415	0.409	300	0.078	0.1409	0.1405	1.1429	1.1365	1.67E-08	-0.0023	0.411	0.1407	1.1387	1.11E-08	0.6020	6.70E-09	
15.08.2024	Zi5 - 2 - 3	32.3	30.2	31.25	3000	0.409	0.402	300	0.078	0.1405	0.1400	1.1365	1.1290	1.96E-08	-0.0023	0.404	0.1402	1.1312	1.40E-08	0.6020	8.43E-09	Zi5 (2)
15.08.2024	Zi5 - 2 - 4	32.3	30.2	31.25	3000	0.402	0.397	300	0.078	0.1400	0.1397	1.1290	1.1237	1.41E-08	-0.0023	0.399	0.1398	1.1258	8.45E-09	0.6020	5.09E-09	Zi5 (2)
15.08.2024	Zi5 - 2 - 5	32.3	30.2	31.25	3000	0.397	0.391	300	0.078	0.1397	0.1392	1.1237	1.1172	1.70E-08	-0.0023	0.393	0.1394	1.1194	1.13E-08	0.6020	6.82E-09	Zi5 (2)
15.08.2024	Zi5 - 3 - 1	31.5	29.7	30.6	900	0.4	0.36	73	0.042	0.1424	0.1396	1.1654	1.1226	4.56E-07	-0.0016	0.362	0.1397	1.1247	4.33E-07	0.6102	2.64E-07	
15.08.2024	Zi5 - 3 - 2	31.5	29.7	30.6	900	0.4	0.36	73	0.042	0.1424	0.1396	1.1654	1.1226	4.56E-07	-0.0016	0.362	0.1397	1.1247	4.33E-07	0.6102	2.64E-07	
15.08.2024	Zi5 - 3 - 3	31.5	29.7	30.6	900	0.4	0.36	71	0.042	0.1424	0.1396	1.1654	1.1226	4.69E-07	-0.0016	0.362	0.1397	1.1247	4.45E-07	0.6102	2.72E-07	Zi5 (3)
15.08.2024	Zi5 - 3 - 4	31.5	29.7	30.6	900	0.4	0.36	72	0.042	0.1424	0.1396	1.1654	1.1226	4.62E-07	-0.0016	0.362	0.1397	1.1247	4.39E-07	0.6102	2.68E-07	Zi5 (3)
15.08.2024	Zi5 - 3 - 5	31.5	29.7	30.6	900	0.4	0.36	71	0.042	0.1424	0.1396	1.1654	1.1226	4.69E-07	-0.0016	0.362	0.1397	1.1247	4.45E-07	0.6102	2.72E-07	Zi5 (3)

Appendix Table 3: Variables – k_f measurements.

6.4. Results: transformed soil properties

Appendix 15 shows the logit formula for transforming relative values between 0 and 1.

$$\text{logit}(p) = \ln \frac{p}{1-p}$$

Appendix 15: formula for logit transformation of variable p (%).

Appendix Table 4 depicts the transformed variables which were used for calculating correlations.

Appendix Table 4: Variable numbers, variable names and applied transformations.

Variable number	Variable name	Applied transformation
1	SHC (k_f)	natural logarithm
2	EC	natural logarithm
3	sand%	logit
4	silt%	logit
5	clay%	logit
6	CEC _{eff, AT} %	logit
7	Na(meq)	natural logarithm
8	K(meq)	natural logarithm
9	Mg(meq)	natural logarithm
10	Ca(meq)	natural logarithm
11	CEC _{eff, INT} %	logit
12	Na(meq%)	logit
13	K(meq%)	logit
14	Mg(meq%)	logit
15	Ca(meq%)	logit
16	SAR	natural logarithm
17	CROSS	natural logarithm
18	Na(H ₂ O)	natural logarithm
19	K(H ₂ O)	natural logarithm
20	Mg(H ₂ O)	natural logarithm
21	Ca(H ₂ O)	natural logarithm
22	Na(H ₂ O%)	logit
23	K(H ₂ O%)	logit
24	Mg(H ₂ O%)	logit
25	Ca(H ₂ O%)	logit
26	salt _{min} %	logit
27	OC%	logit
28	IC%	logit
29	WC	logit

Appendix Table 5: Variable numbers 1 – 14 transformed values on each site.

depth	site	Variable number													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
Topsoil	Ma1	-21.140	6.551	-0.498	-0.892	-0.703	5.513	4.425	2.534	4.040	5.508	5.990	-1.331	-3.442	-1.799
	Ma2	-20.463	6.605	-1.015	-0.397	-0.700	5.328	4.094	2.389	3.967	5.382	5.832	-1.544	-3.409	-1.696
	Ma3	-19.377	6.553	-1.551	-0.020	-0.708	5.300	3.955	2.092	3.938	5.433	5.830	-1.711	-3.705	-1.727
	Ma4	-15.539	6.001	-0.619	-0.315	-1.220	4.214	2.128	1.887	3.484	4.288	4.790	-2.602	-2.844	-0.990
	Ma5	-13.389	6.617	0.036	-1.306	-0.955	4.374	1.649	1.526	3.122	4.758	5.004	-3.317	-3.442	-1.719
	Mo1	-19.228	6.157	-0.754	-0.852	-0.485	5.276	3.300	2.580	4.688	5.307	5.860	-2.484	-3.231	-0.800
	Mo2	-12.733	6.717	-0.435	-0.299	-1.508	4.067	2.625	1.887	3.500	3.757	4.567	-1.782	-2.602	-0.650
	Mo3	-14.379	6.111	-0.233	-1.230	-0.700	4.265	1.946	2.282	3.930	4.057	4.832	-2.825	-2.470	-0.385
	Mo4	-15.475	6.525	-0.768	-0.398	-0.939	4.447	2.028	2.163	4.130	4.332	5.041	-2.966	-2.806	-0.397
	Mo5	-13.982	6.131	-1.355	0.255	-1.200	4.540	2.092	2.272	4.089	4.524	5.134	-2.987	-2.806	-0.610
	Zi1	-18.429	7.252	-1.020	-1.067	-0.084	4.016	2.322	1.163	3.584	3.875	4.581	-2.154	-3.378	-0.537
	Zi2	-17.804	6.918	-0.088	-1.440	-0.706	4.355	2.625	1.411	3.869	4.275	4.925	-2.197	-3.476	-0.628
	Zi3	-17.686	7.091	-0.722	-0.645	-0.714	5.578	3.955	2.416	5.310	5.297	6.143	-2.070	-3.705	-0.261
	Zi4	-17.757	7.687	-2.966	-0.102	-0.095	5.428	4.485	2.332	4.488	5.126	5.875	-1.104	-3.511	-1.099
	Zi5	-16.137	6.939	-3.127	-0.290	0.120	5.080	3.955	2.128	4.430	4.758	5.565	-1.386	-3.409	-0.745
Subsoil	Ma1		6.823	-0.072	-0.750	-1.405	4.369	2.797	1.253	2.588	4.652	4.927	-2.002	-3.664	-2.231
	Ma2		6.639	-0.954	-0.214	-0.968	4.251	2.681	0.993	2.907	4.470	4.812	-2.002	-3.794	-1.750
	Ma3		6.933	-0.619	-0.490	-0.995	3.998	2.485	0.833	2.625	4.197	4.550	-1.928	-3.664	-1.766
	Mo1		6.263	-0.201	-1.150	-0.802	5.280	3.063	1.932	4.642	5.448	5.898	-2.769	-3.944	-0.920
	Mo2		6.075	0.048	-1.900	-0.585	5.245	2.845	2.116	4.488	5.477	5.868	-2.966	-3.749	-1.093
	Mo3		6.078	0.225	-1.777	-0.850	5.048	2.815	1.629	4.430	5.214	5.668	-2.788	-4.057	-0.895
	Mo4		5.823	0.104	-1.382	-0.978	5.205	2.152	1.792	4.592	5.466	5.858	-3.664	-4.057	-0.935
	Mo5		5.953	0.663	-3.058	-0.871	3.195	1.194	0.336	2.549	3.281	3.786	-2.527	-3.442	-0.891
	Zi1		7.639	0.048	-1.994	-0.540	6.002	4.648	2.646	5.234	5.951	6.537	-1.727	-3.892	-0.984
	Zi2		7.763	-0.364	-1.428	-0.420	5.997	4.648	2.485	5.123	6.002	6.534	-1.719	-4.057	-1.131
	Zi3		7.737	-0.800	-1.078	-0.257	6.058	4.648	2.625	5.529	5.906	6.603	-1.799	-3.944	-0.654
	Zi4		8.048	-2.556	-0.574	0.272	6.108	5.020	2.580	5.123	5.997	6.599	-1.349	-3.999	-1.214
	Zi5		6.765	-1.974	-0.710	0.195	5.256	3.666	1.758	4.488	5.322	5.825	-2.031	-4.057	-1.036

Appendix Table 6: Variable numbers 15 – 29 transformed values on each site.

depth	site	Variable number														
		15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
Topsoil	Ma1	0.477	-0.734	-0.616	4.137	1.459	1.131	1.308	1.742	-2.788	-3.127	-2.944	-5.989	-6.073	-4.034	-1.266
	Ma2	0.562	-0.994	-0.868	4.094	1.435	1.131	0.956	1.799	-2.752	-3.079	-3.231	-6.030	-6.117	-4.005	-1.516
	Ma3	0.717	-1.171	-1.050	3.850	1.281	1.131	1.589	1.399	-2.734	-2.883	-2.389	-6.213	-6.117	-3.966	-2.442
	Ma4	0.426	-2.526	-2.040	4.218	1.099	1.686	2.827	0.984	-3.378	-2.788	-1.510	-5.806	-4.846	-4.269	-2.091
	Ma5	1.277	-3.219	-2.659	4.177	0.833	1.482	3.127	0.791	-3.664	-3.009	-1.153	-5.806	-3.771	-4.314	-3.476
	Mo1	0.302	-1.897	-1.561	3.025	1.686	1.902	2.241	-0.040	-1.919	-1.673	-1.243	-6.644	-5.840	-3.350	-2.091
	Mo2	-0.225	-1.833	-1.514	2.625	1.361	2.067	2.595	-0.597	-2.208	-1.368	-0.650	-6.811	-4.713	-3.745	-1.266
	Mo3	-0.160	-2.659	-2.040	1.792	1.308	2.262	2.370	-1.386	-1.964	-0.754	-0.588	-7.130	-5.110	-3.627	-2.091
	Mo4	-0.032	-2.813	-2.120	2.054	1.386	2.549	2.779	-1.437	-2.220	-0.777	-0.426	-6.811	-4.668	-3.581	-1.815
	Mo5	0.172	-2.659	-2.120	1.705	1.224	2.342	2.660	-1.636	-2.186	-0.805	-0.294	-7.012	-4.626	-3.522	-1.735
	Zi1	-0.024	-2.207	-1.966	4.004	2.152	2.128	1.482	0.940	-2.060	-2.091	-2.788	-5.950	-5.355	-2.934	
	Zi2	0.088	-2.040	-1.833	3.459	1.917	2.067	1.723	0.452	-1.901	-1.719	-2.111	-6.375	-5.651	-3.265	
	Zi3	-0.286	-1.347	-1.109	4.004	1.917	2.510	1.841	0.772	-2.389	-1.704	-2.470	-5.950	-5.596	-3.071	-1.450
	Zi4	-0.112	-0.598	-0.462	4.648	1.808	1.856	1.504	1.807	-2.924	-2.883	-3.259	-5.468	-4.984	-2.944	-1.516
	Zi5	-0.217	-0.994	-0.821	3.850	1.224	1.649	1.224	1.368	-2.788	-2.338	-2.806	-6.213	-4.690	-2.905	-1.658
Subsoil	Ma1	1.147	-1.897	-1.772	3.666	1.504	1.131	1.099	1.313	-2.314	-2.717	-2.752	-6.375	-6.907	-3.483	
	Ma2	0.900	-1.966	-1.833	3.733	1.194	1.131	1.988	1.120	-2.769	-2.825	-1.883	-6.318	-6.907	-2.985	
	Ma3	0.857	-2.040	-1.897	3.850	1.281	1.131	1.589	1.399	-2.717	-2.883	-2.389	-6.213	-7.264	-3.413	
	Mo1	0.567	-2.120	-1.897	2.918	1.065	2.041	2.493	-0.201	-2.571	-1.476	-0.876	-6.724	-7.012	-3.125	
	Mo2	0.740	-2.303	-2.040	2.442	1.030	1.589	2.293	-0.422	-2.254	-1.586	-0.668	-7.012	-6.570	-3.446	
	Mo3	0.554	-2.303	-2.040	2.815	1.163	1.932	2.219	-0.148	-2.326	-1.437	-1.072	-6.811	-6.811	-3.446	
	Mo4	0.735	-2.996	-2.659	1.872	1.131	2.041	2.534	-1.277	-2.143	-1.067	-0.319	-7.130	-7.264	-3.413	
	Mo5	0.422	-2.996	-2.659	2.734	1.459	1.825	2.197	-0.233	-1.964	-1.537	-1.056	-6.811	-7.824	-4.088	
	Zi1	0.229	-0.821	-0.693	4.361	1.932	1.099	1.589	1.666	-2.527	-3.409	-2.903	-5.741	-6.570	-3.299	
	Zi2	0.352	-0.821	-0.713	4.597	1.526	1.131	0.262	2.402	-3.103	-3.511	-4.411	-5.569	-7.130	-3.413	
	Zi3	-0.008	-0.868	-0.713	4.543	1.808	1.482	0.588	2.021	-2.788	-3.127	-4.057	-5.596	-6.164	-3.170	
	Zi4	0.189	-0.462	-0.342	4.871	1.589	1.131	0.956	2.512	-3.317	-3.794	-3.999	-5.314	-5.875	-2.887	
	Zi5	0.426	-1.470	-1.347	3.523	1.335	1.775	2.092	0.641	-2.527	-2.051	-1.681	-6.375	-5.623	-3.034	

6.5. Results: PCA – Principal components

Appendix Table 7 and Appendix Table 8 show numerical results of relevant principal components for topsoil and subsoil properties.

Appendix Table 7: Numerical results of relevant PC for topsoil properties.

Soda pan	Site	PC1 _{up}	PC2 _{up}	PC3 _{up}	PC4 _{up}
Martenhoflacke	Ma1	5.026	-2.543	1.588	-0.488
	Ma2	4.427	-2.542	1.143	-0.805
	Ma3	3.758	-2.948	1.031	-0.324
	Ma4	-3.198	-3.360	-0.151	-1.364
	Ma5	-4.092	-7.165	-1.505	1.774
Moschadolacke	Mo1	0.436	0.993	2.493	3.036
	Mo2	-3.733	1.324	-0.141	-3.138
	Mo3	-5.144	2.361	1.477	-0.319
	Mo4	-4.522	2.165	1.432	0.079
	Mo5	-4.412	1.538	2.699	-0.352
Illmitzer Zicksee	Zi1	-0.895	1.852	-5.556	0.183
	Zi2	-1.183	0.975	-3.233	1.814
	Zi3	3.587	3.608	0.825	2.469
	Zi4	6.285	1.693	-1.237	-1.103
	Zi5	3.662	2.050	-0.865	-1.463

Appendix Table 8: Numerical results of relevant PC for subsoil properties.

Soda pan	Site	PC1 _{low}	PC2 _{low}	PC3 _{low}
Martenhoflacke	Ma1	-2.077	-4.657	-0.916
	Ma2	-1.326	-3.459	-2.743
	Ma3	-2.205	-4.441	-0.567
	Ma4			
	Ma5			
Moschadolacke	Mo1	-1.685	2.946	-0.910
	Mo2	-2.791	2.444	-0.584
	Mo3	-2.554	2.758	-0.148
	Mo4	-4.435	4.210	-1.481
	Mo5	-7.955	-1.458	4.399
Illmitzer Zicksee	Zi1	4.300	0.592	2.760
	Zi2	5.147	-0.318	1.483
	Zi3	5.911	0.960	1.542
	Zi4	7.892	-0.897	-0.897
	Zi5	1.779	1.317	-1.940

6.6. Results: PCA factor correlations

The following Appendix Table 9 and Appendix Table 10 show upper and subsoil property correlations with Principal Components. A permutational test was performed to obtain p (N = 10000).

Appendix Table 9: Topsoil properties PCA - correlations with Principal Components ($p < 0.05^{***}$, $p < 0.1^{**}$).

PC1			PC2			PC3			PC4		
Soil property	r	R ²	Soil property	r	R ²	Soil property	r	R ²	Soil property	r	R ²
pH	0.83***	0.689	pH	0.390	0.152	pH	-0.207	0.043	pH	-0.024	0.001
EC	0.546**	0.298	EC	0.290	0.084	EC	-0.63***	0.397	EC	-0.028	0.001
sand%	-0.574**	0.329	sand%	-0.293	0.086	sand%	0.045	0.002	sand%	0.359	0.129
silt%	0.22	0.048	silt%	0.126	0.016	silt%	0.427	0.182	silt%	-0.541***	0.293
clay%	0.601***	0.361	clay%	0.284	0.081	clay%	-0.395	0.156	clay%	0.176	0.031
CECeff.AT	0.87***	0.757	CECeff.AT	0.001	0.000	CECeff.AT	0.427	0.182	CECeff.AT	0.221	0.049
Na(mol%)	0.87***	0.757	Na(mol%)	0.132	0.017	Na(mol%)	-0.138	0.019	Na(mol%)	-0.385**	0.148
K(mol%)	-0.835***	0.698	K(mol%)	0.190	0.036	K(mol%)	0.293	0.086	K(mol%)	-0.337	0.114
Mg(mol%)	-0.51***	0.260	Mg(mol%)	0.799***	0.639	Mg(mol%)	-0.093	0.009	Mg(mol%)	0.183	0.033
Ca(mol%)	-0.198	0.039	Ca(mol%)	-0.892***	0.796	Ca(mol%)	0.065	0.004	Ca(mol%)	0.343	0.118
Na(meq)	0.972***	0.945	Na(meq)	0.083	0.007	Na(meq)	0.163	0.027	Na(meq)	-0.081	0.007
K(meq)	0.407	0.166	K(meq)	0.184	0.034	K(meq)	0.865***	0.748	K(meq)	-0.010	0.000
Mg(meq)	0.531	0.282	Mg(meq)	0.62***	0.385	Mg(meq)	0.374	0.140	Mg(meq)	0.367	0.135
Ca(meq)	0.775***	0.601	Ca(meq)	-0.286	0.082	Ca(meq)	0.446	0.199	Ca(meq)	0.326	0.106
CECeff.INT	0.839***	0.703	CECeff.INT	-0.013	0.000	CECeff.INT	0.447	0.200	CECeff.INT	0.286	0.082
Na(meq%)	0.861***	0.741	Na(meq%)	0.142	0.020	Na(meq%)	-0.129	0.017	Na(meq%)	-0.403**	0.163
K(meq%)	-0.774***	0.599	K(meq%)	0.224	0.050	K(meq%)	0.300	0.090	K(meq%)	-0.423	0.179
Mg(meq%)	-0.438***	0.192	Mg(meq%)	0.853***	0.727	Mg(meq%)	-0.102	0.010	Mg(meq%)	0.115	0.013
Ca(meq%)	-0.018	0.000	Ca(meq%)	-0.949***	0.900	Ca(meq%)	0.079	0.006	Ca(meq%)	0.227	0.051
SAR	0.944***	0.891	SAR	0.134	0.018	SAR	0.056	0.003	SAR	-0.233	0.055
CROSS	0.925***	0.856	CROSS	0.169	0.029	CROSS	0.147	0.022	CROSS	-0.267	0.071
Na(H ₂ O)	0.694***	0.482	Na(H ₂ O)	-0.439**	0.193	Na(H ₂ O)	-0.452**	0.204	Na(H ₂ O)	0.053	0.003
K(H ₂ O)	0.361	0.130	K(H ₂ O)	0.607	0.368	K(H ₂ O)	-0.431	0.186	K(H ₂ O)	0.320	0.102
Mg(H ₂ O)	-0.526***	0.276	Mg(H ₂ O)	0.758***	0.575	Mg(H ₂ O)	-0.042	0.002	Mg(H ₂ O)	0.208	0.043
Ca(H ₂ O)	-0.848***	0.719	Ca(H ₂ O)	-0.171	0.029	Ca(H ₂ O)	0.205	0.042	Ca(H ₂ O)	0.092	0.008
Na(H ₂ O%)	0.815***	0.664	Na(H ₂ O%)	-0.417	0.174	Na(H ₂ O%)	-0.348	0.121	Na(H ₂ O%)	-0.041	0.002
K(H ₂ O%)	-0.213	0.045	K(H ₂ O%)	0.767	0.589	K(H ₂ O%)	0.050	0.002	K(H ₂ O%)	0.199**	0.040
Mg(H ₂ O%)	-0.645***	0.416	Mg(H ₂ O%)	0.7***	0.490	Mg(H ₂ O%)	0.236	0.056	Mg(H ₂ O%)	0.097	0.009
Ca(H ₂ O%)	-0.896***	0.803	Ca(H ₂ O%)	0.085	0.007	Ca(H ₂ O%)	0.377	0.142	Ca(H ₂ O%)	0.025	0.001
salt _{min} %	0.617***	0.381	salt _{min} %	-0.420	0.176	salt _{min} %	-0.46***	0.212	salt _{min} %	0.051	0.003
OC%	-0.609***	0.371	OC%	-0.093	0.009	OC%	-0.165	0.027	OC%	-0.187	0.035
IC%	0.276	0.076	IC%	0.831***	0.691	IC%	-0.351	0.123	IC%	0.161	0.026
>2mm%	-0.304	0.092	>2mm%	-0.477***	0.228	>2mm%	-0.192	0.037	>2mm%	0.63**	0.396

Appendix Table 10: Subsoil properties PCA - correlations with Principal Components ($p < 0.05^{***}$, $p < 0.1^{**}$).

PC1			PC2			PC3		
Soil property	r	R ²	Soil property	r	R ²	Soil property	r	R ²
pH	0.788***	0.621	pH	-0.548**	0.301	pH	-0.118	0.014
EC	0.927***	0.859	EC	-0.317	0.101	EC	0.174	0.030
sand%	-0.665***	0.442	sand%	0.162	0.026	sand%	0.477	0.228
silt%	0.396	0.157	silt%	-0.375	0.141	silt%	-0.793***	0.629
clay%	0.722***	0.521	clay%	0.294	0.087	clay%	0.016	0.000
CECeff, AT	0.832***	0.693	CECeff, AT	0.503	0.253	CECeff, AT	-0.049	0.002
Na(mol%)	0.737***	0.543	Na(mol%)	-0.612***	0.375	Na(mol%)	0.157	0.025
K(mol%)	-0.752***	0.565	K(mol%)	-0.436	0.190	K(mol%)	0.335	0.112
Mg(mol%)	0.039	0.002	Mg(mol%)	0.861***	0.741	Mg(mol%)	0.384	0.148
Ca(mol%)	-0.779***	0.608	Ca(mol%)	-0.099	0.010	Ca(mol%)	-0.498**	0.248
Na(meq)	0.986***	0.972	Na(meq)	0.095	0.009	Na(meq)	0.042	0.002
K(meq)	0.811***	0.658	K(meq)	0.496	0.246	K(meq)	0.031	0.001
Mg(meq)	0.698***	0.487	Mg(meq)	0.704	0.496	Mg(meq)	0.089	0.008
Ca(meq)	0.773***	0.598	Ca(meq)	0.537	0.288	Ca(meq)	-0.14	0.019
CECeff, INT	0.805***	0.648	CECeff, INT	0.541	0.293	CECeff, INT	-0.058	0.003
Na(meq%)	0.735***	0.541	Na(meq%)	-0.615***	0.378	Na(meq%)	0.158	0.025
K(meq%)	-0.567	0.322	K(meq%)	-0.615***	0.378	K(meq%)	0.362	0.131
Mg(meq%)	0.146	0.021	Mg(meq%)	0.819***	0.670	Mg(meq%)	0.428	0.183
Ca(meq%)	-0.641***	0.411	Ca(meq%)	-0.39	0.152	Ca(meq%)	-0.529***	0.280
SAR	0.977***	0.954	SAR	-0.152	0.023	SAR	0.08	0.006
CROSS	0.982***	0.964	CROSS	-0.108	0.012	CROSS	0.111	0.012
Na(H ₂ O)	0.856***	0.734	Na(H ₂ O)	-0.473**	0.223	Na(H ₂ O)	0.164	0.027
K(H ₂ O)	0.639***	0.408	K(H ₂ O)	-0.267	0.071	K(H ₂ O)	0.589	0.347
Mg(H ₂ O)	-0.527***	0.278	Mg(H ₂ O)	0.747***	0.557	Mg(H ₂ O)	-0.033	0.001
Ca(H ₂ O)	-0.737***	0.543	Ca(H ₂ O)	0.42***	0.176	Ca(H ₂ O)	-0.257	0.066
Na(H ₂ O%)	0.82***	0.673	Na(H ₂ O%)	-0.544**	0.296	Na(H ₂ O%)	0.14	0.020
K(H ₂ O%)	-0.847***	0.717	K(H ₂ O%)	0.245	0.060	K(H ₂ O%)	0.196	0.038
Mg(H ₂ O%)	-0.807***	0.651	Mg(H ₂ O%)	0.549***	0.301	Mg(H ₂ O%)	-0.13	0.017
Ca(H ₂ O%)	-0.838***	0.703	Ca(H ₂ O%)	0.421**	0.177	Ca(H ₂ O%)	-0.233	0.054
salt _{min} %	0.902***	0.814	salt _{min} %	-0.357**	0.128	salt _{min} %	0.203	0.041
OC%	0.709***	0.502	OC%	0.189	0.036	OC%	-0.35	0.122
IC%	0.673***	0.453	IC%	0.08	0.006	IC%	-0.659	0.435
>2mm%	-0.372**	0.138	>2mm%	0.191	0.037	>2mm%	0.532	0.283

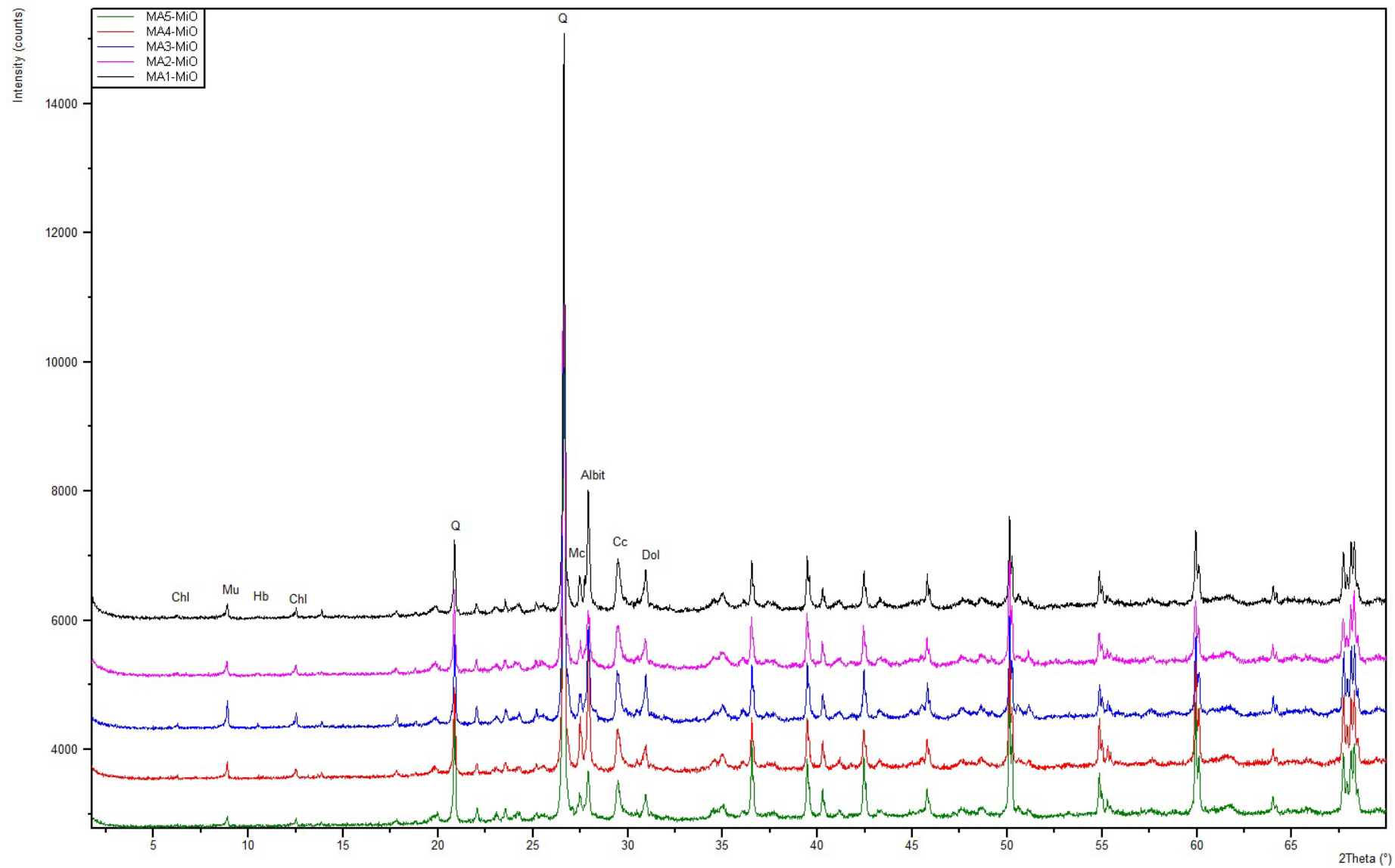
6.7. Results: soil mineralogy

6.7.1. Bulk soil mineralogy

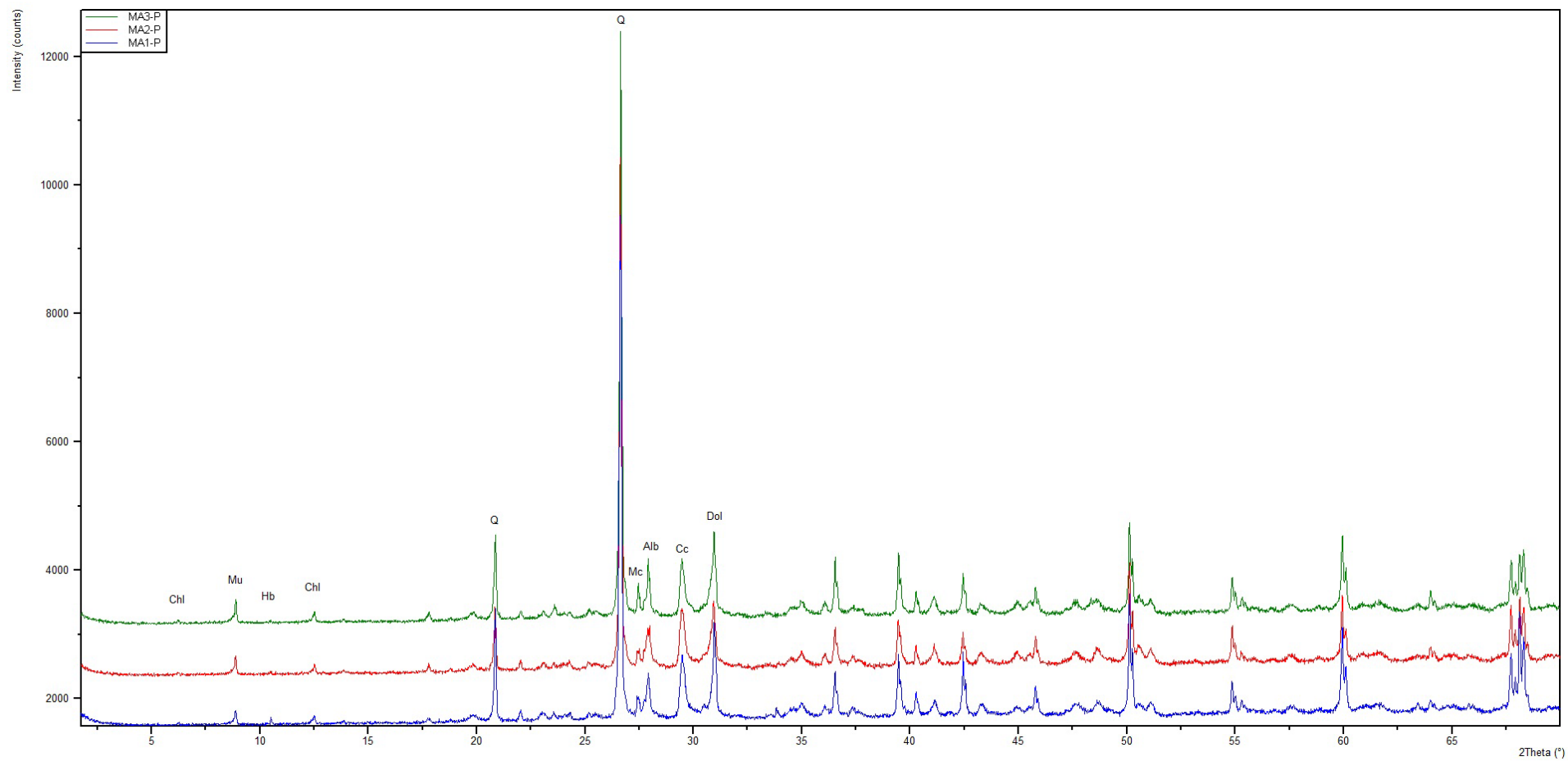
The following X-ray diffraction patterns, Appendix 16 - Appendix 21 show the mineralogy for soils at all measurement sites. Appendix Table 11 gives an overview of used abbreviations and mineral names.

Appendix Table 11: Abbreviations and mineral names – total bulk soil mineralogy

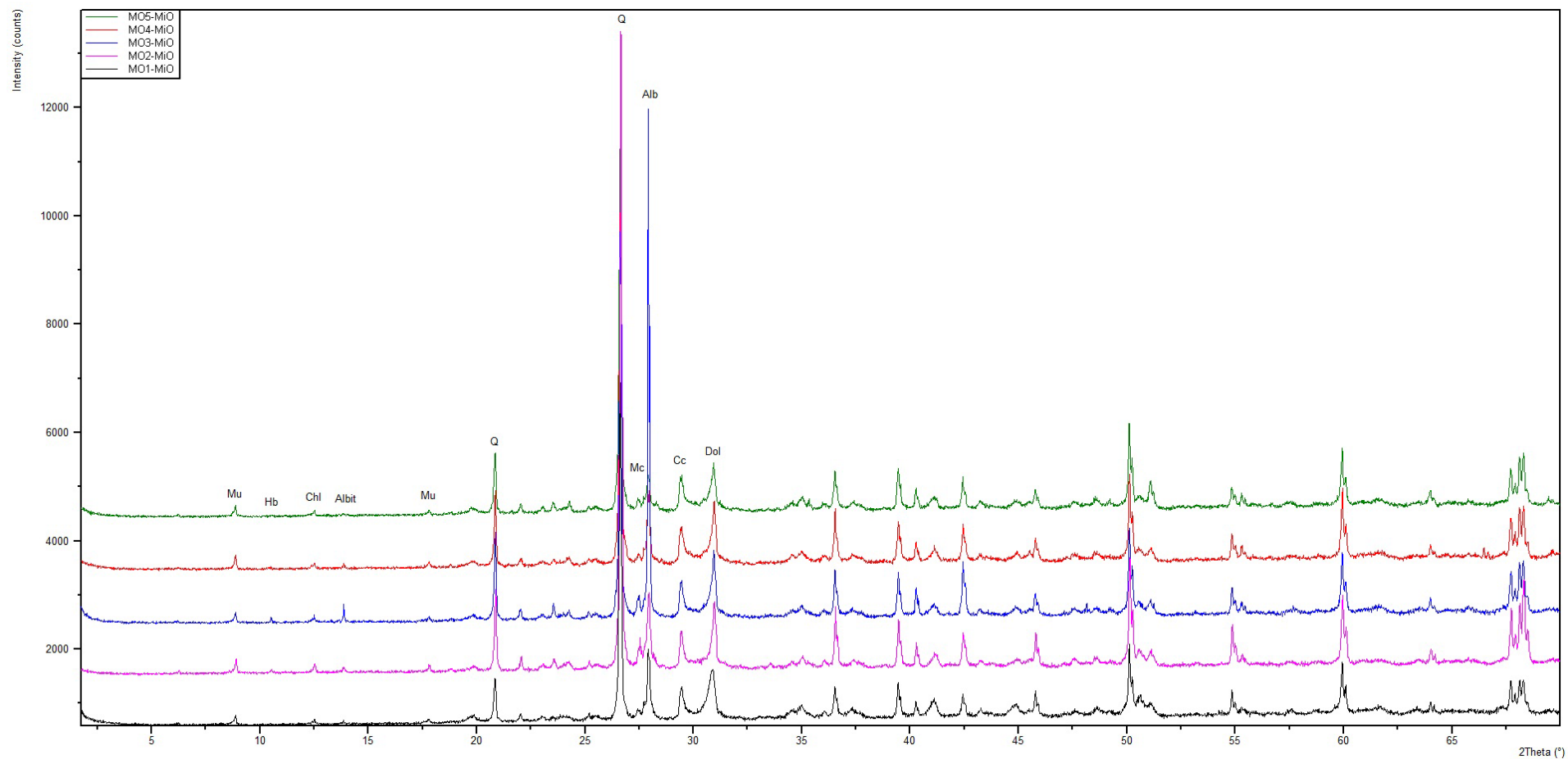
Abbreviation	Mineral
Chl	Chlorite
Mu	Muscovite
Hb	Hornblende
Q	Quartz
Mc	Microcline
Albit	Albite
Cc	Calcite
Dol	Dolomite



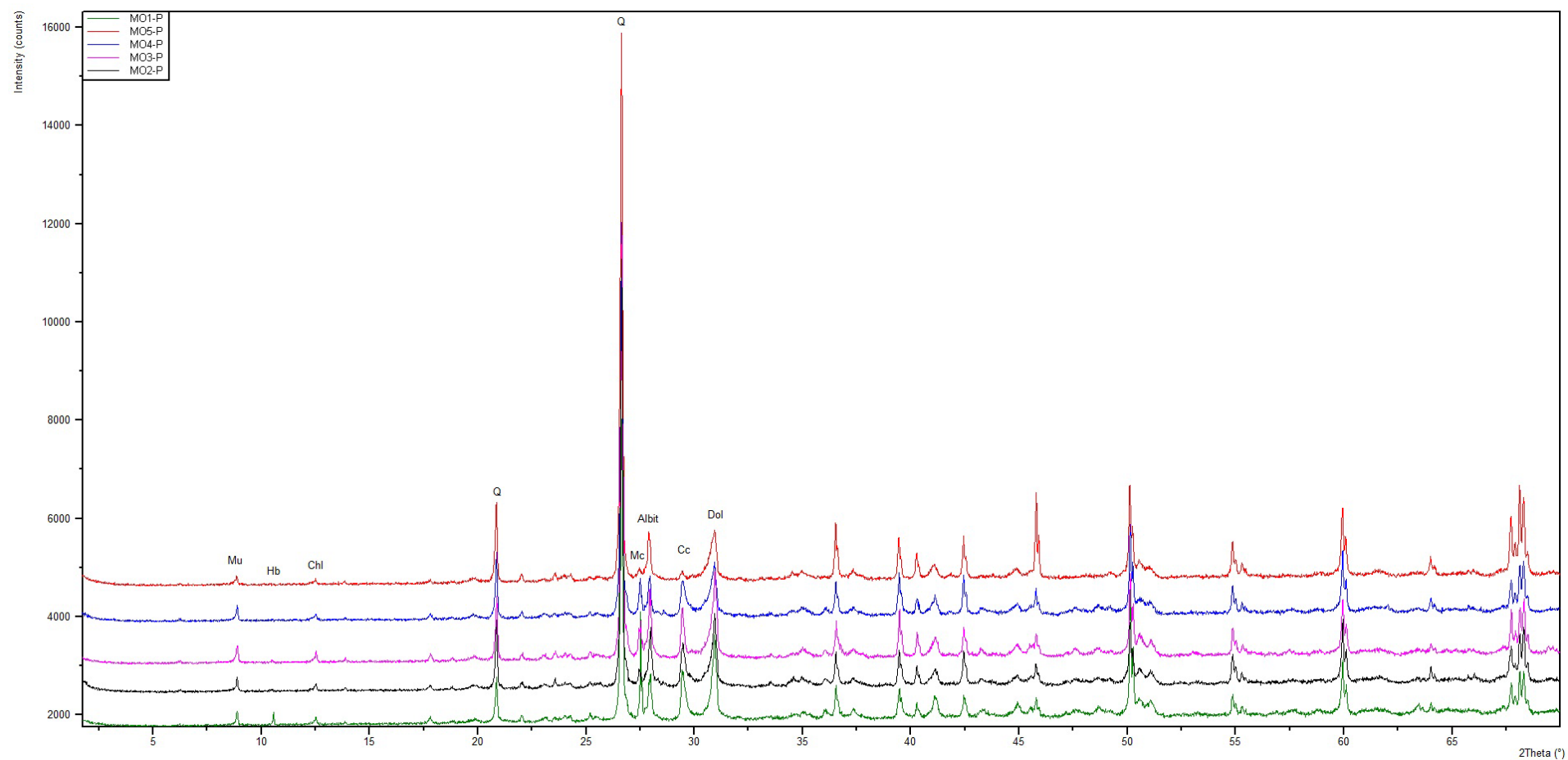
Appendix 16: Bulk soil mineralogy - topsoil Martenhoflacke



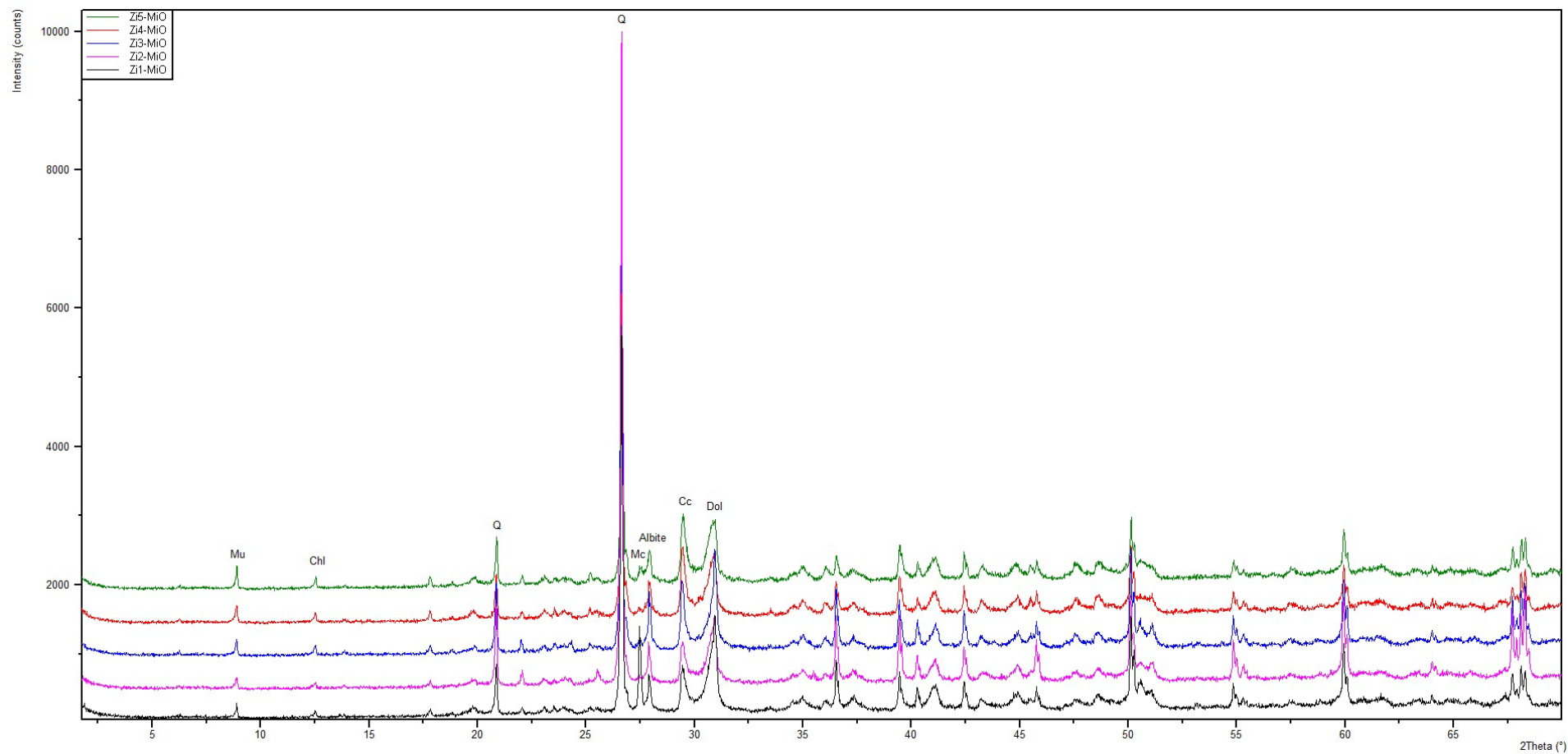
Appendix 17: Bulk soil mineralogy - subsoil Martenhoflacke



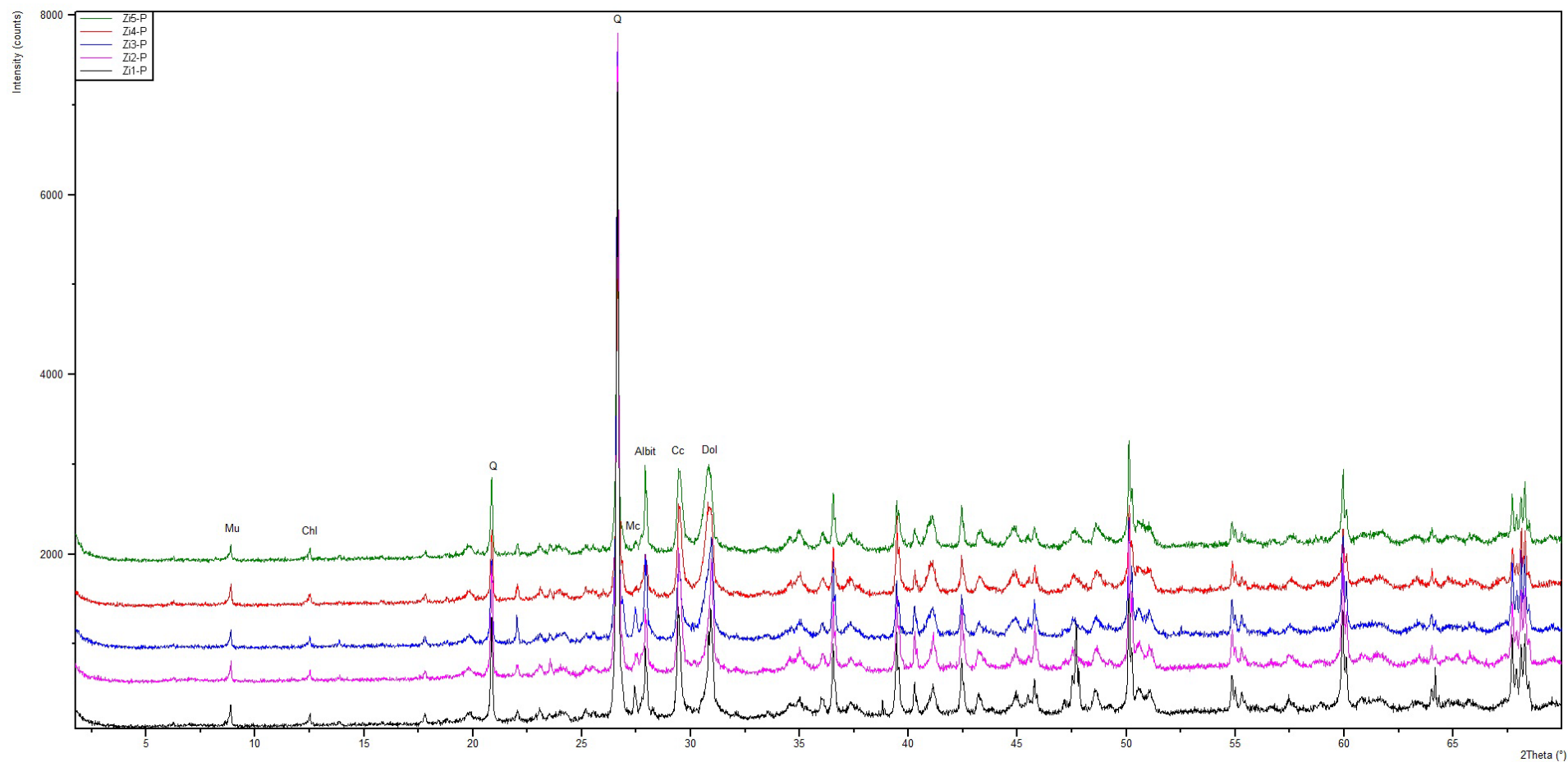
Appendix 18: Bulk soil mineralogy - topsoil Moschadolacke



Appendix 19: Bulk soil mineralogy - subsoil Moschadolacke



Appendix 20: Bulk soil mineralogy - topsoil Illmitzer Zicksee



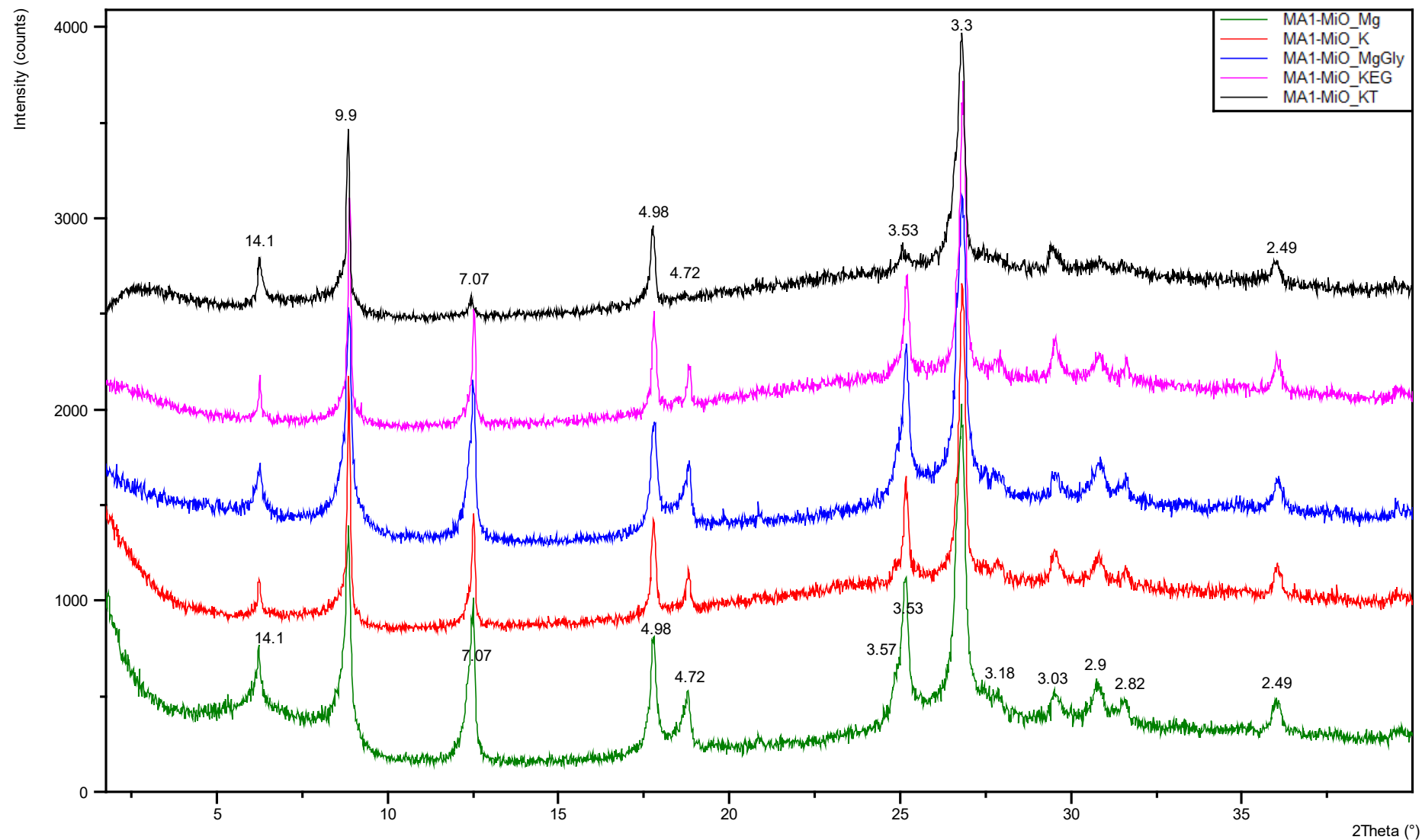
Appendix 21 Bulk soil mineralogy - subsoil Illmitzer Zicksee

6.7.2. Clay mineralogy

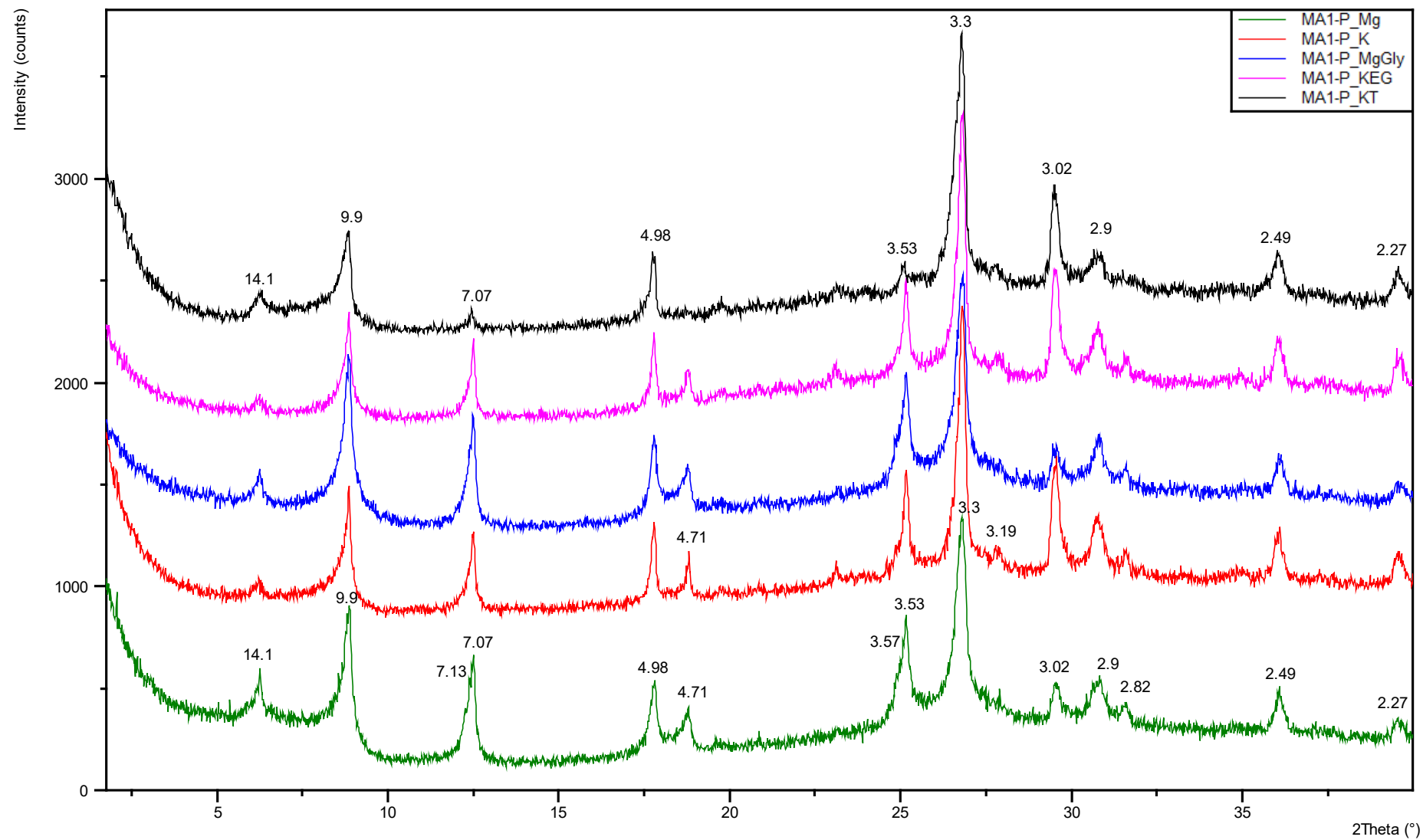
The following X-ray diffraction patterns, Appendix 23 - Appendix 27 show the mineralogy of clay fraction <0.2 μm (clay) at all measurement sites. Appendix Table 12 gives an overview on of the d-values and corresponding minerals. All samples contain chlorite and illite and small amounts of kaolinite. Sample Zi1 additionally contains smectite.

Appendix Table 12: Signals (2Theta) and corresponding minerals

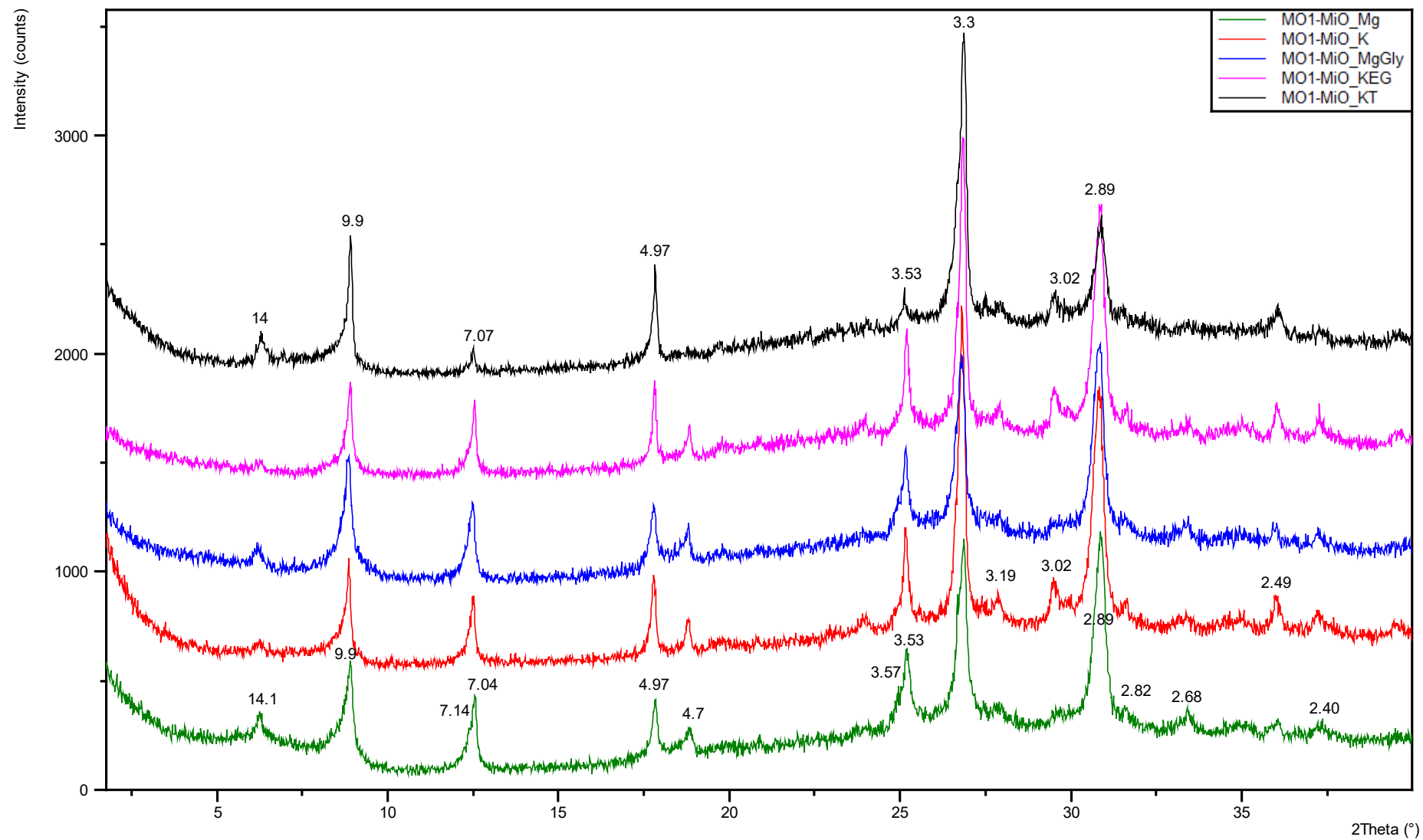
d-value (Å)	Corresponding minerals
2.9	Protodolomite
3.03	Calcite
3.3	Illite
3.53	Chlorite
3.57	Kaolinite
4.72	Chlorite
4.98	Illite
7.07	Chlorite/kaolinite
9.9	Illite
14.1	Chlorite
~17	Smectite (blue line – Mg^{2+} and glycerol saturation)



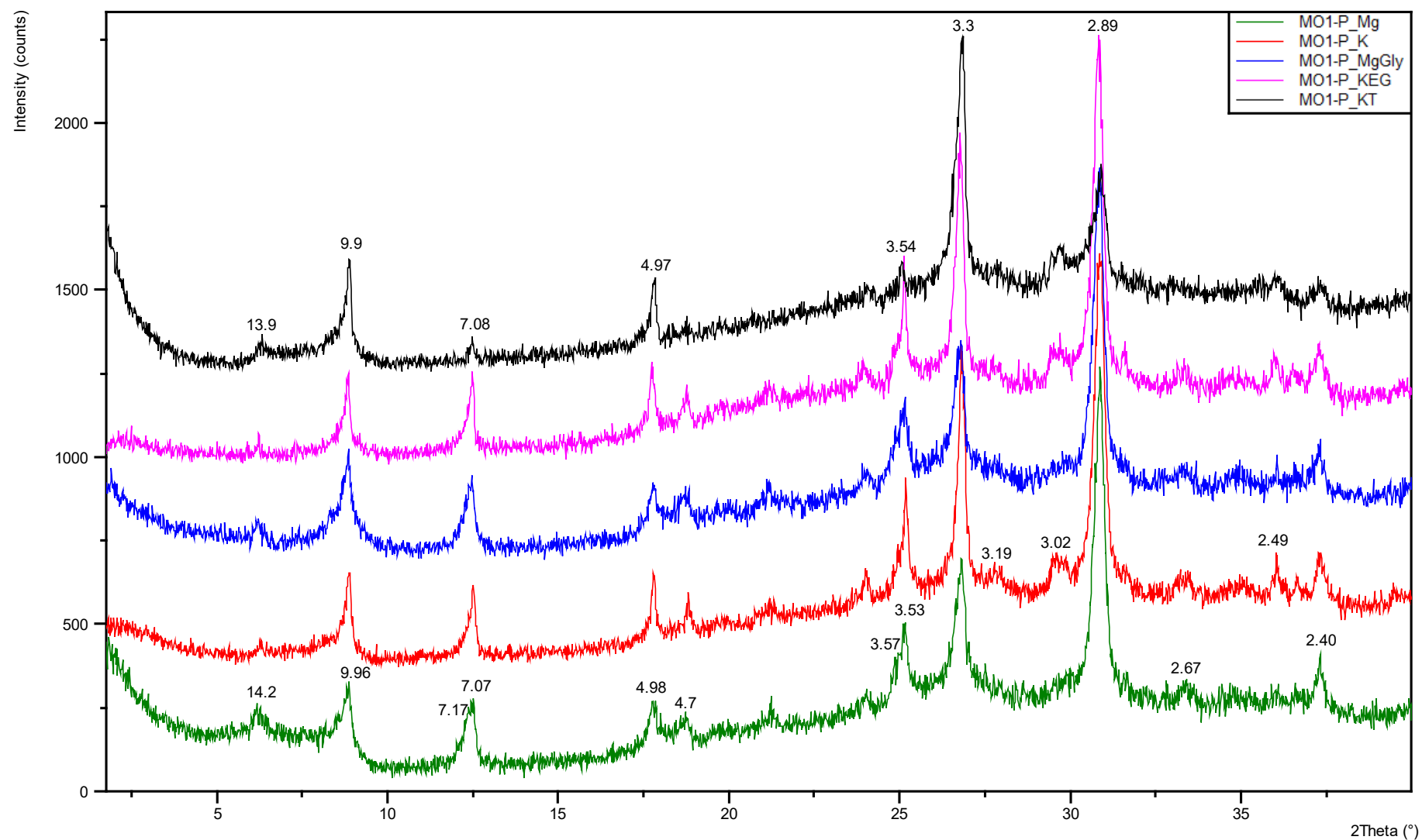
Appendix 22 Clay mineralogy - site Ma1, topsoil. X-ray diffraction patterns of the clay fraction, saturated with Mg, K, Mg and glycerol, K and ethylene glycol, and heated to 550 °C; d-values in Å.



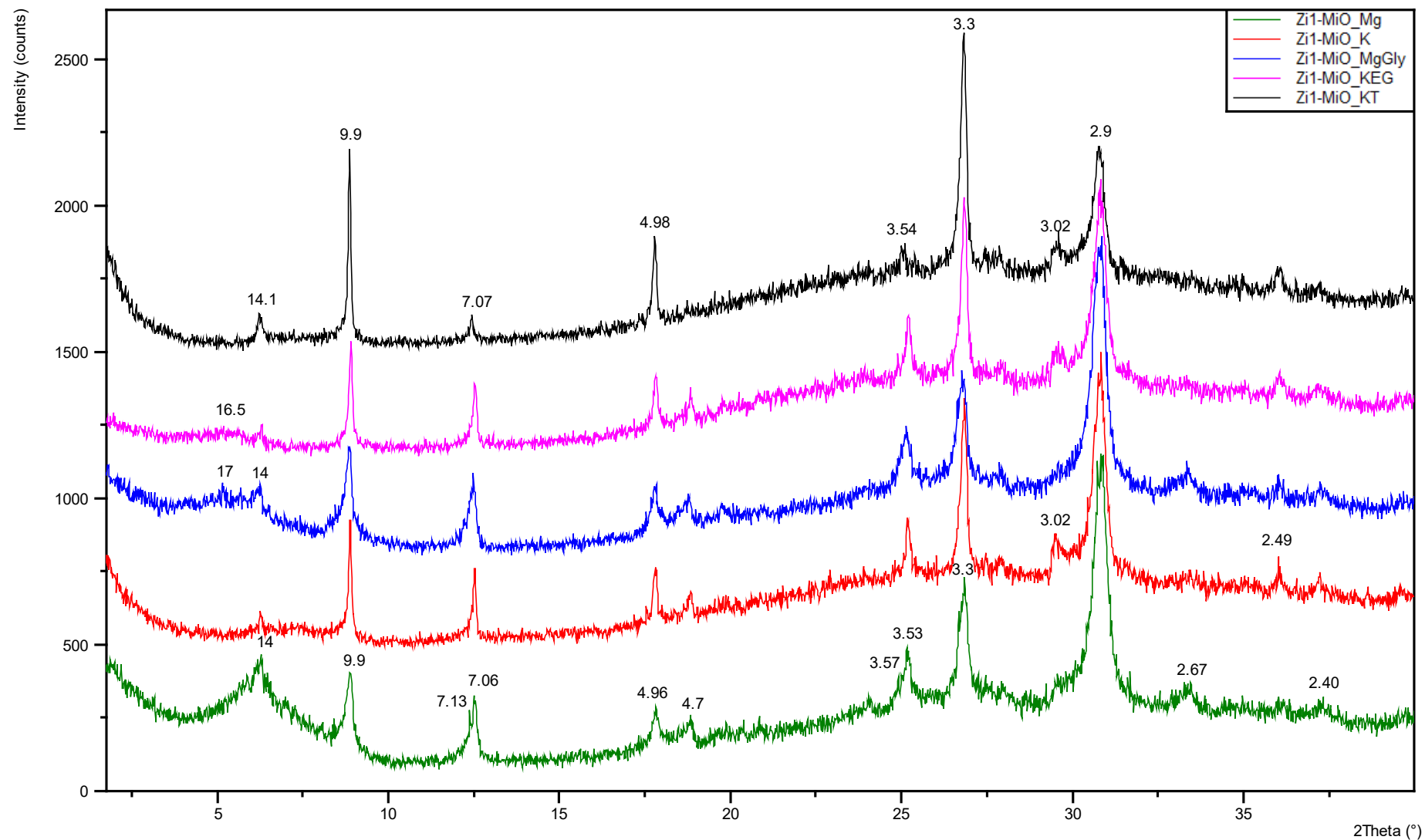
Appendix 23 Clay mineralogy - site Ma1, subsoil. X-ray diffraction patterns of the clay fraction, saturated with Mg, K, Mg and glycerol, K and ethylene glycol, and heated to 550 °C; d-values in Å.



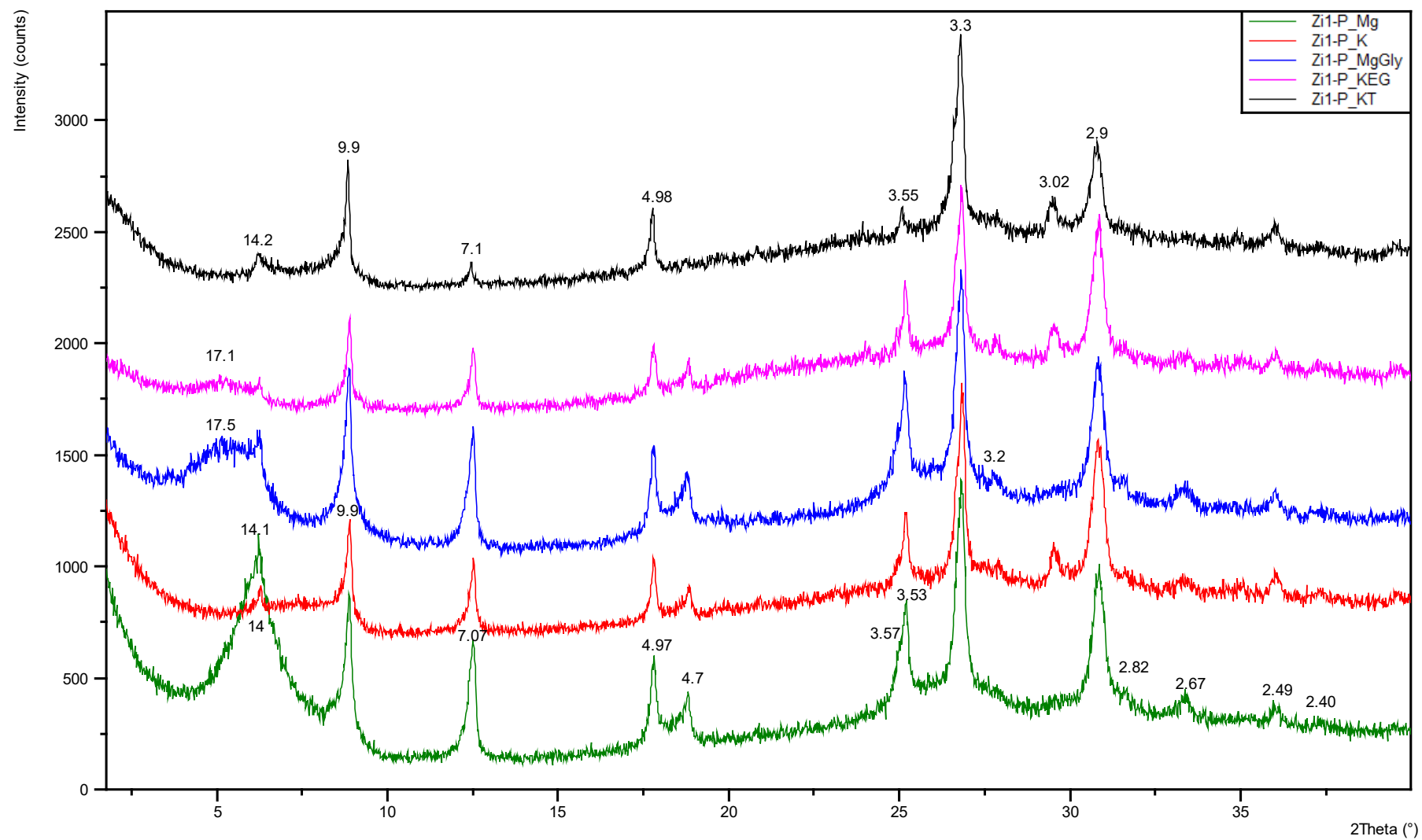
Appendix 24 Clay mineralogy - site Mo1, topsoil. X-ray diffraction patterns of the clay fraction, saturated with Mg, K, Mg and glycerol, K and ethylene glycol, and heated to 550 °C; d-values in Å.



Appendix 25 Clay mineralogy - site Mo1, subsoil. X-ray diffraction patterns of the clay fraction, saturated with Mg, K, Mg and glycerol, K and ethylene glycol, and heated to 550 °C; d-values in Å.



Appendix 26 Clay mineralogy - site Zi1, topsoil. X-ray diffraction patterns of the clay fraction, saturated with Mg, K, Mg and glycerol, K and ethylene glycol, and heated to 550 °C; d-values in Å.



Appendix 27 Clay mineralogy - site Zi1, subsoil. X-ray diffraction patterns of the clay fraction, saturated with Mg, K, Mg and glycerol, K and ethylene glycol, and heated to 550 °C; d-values in Å.