Effects of soil erosion on soil characteristics and productivity

Dedicated to Univ. Prof. Dipl.-Ing. Dr. Dr. h.c. Winfried E. H. Blum on the occasion of his 60^{th} birthday

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Die Wirkung von Bodenerosion auf Bodeneigenschaften und Bodenproduktivität

Univ. Prof. Dipl.-Ing. Dr. Dr. h.c. Winfried E. H. Blum zu seinem 60. Geburtstag gewidmet

1. Introduction

Soil erosion is a major agent of landscape formation. In many landscapes, soil characteristics and soil quality are influenced by the way runoff water flows over the soil surface causing erosion and sedimentation of soil particles. With respect to the ability of soil to produce food (BLUM, 1994), three main causes of soil quality deterioration may be identified, not necessarily independent of each other. These are:

i) loss of fertile topsoil
ii) reduced amount of water available to the plant
iii) structural degradation of soil.

The erosive power of runoff increases with the length and slope of the hillside (MOORE and BURCH, 1986). Therefore soil quality in general and soil chemical and physical properties in particular should also change at different positions on the hillside, depending on the magnitude of erosion and sedimentation. Changes in the content of organic matter and nutrients, pH values, soil texture and available water capacity at different positions in the landscape have been reported by various authors (FRYE et al., 1982; MALO et al., 1974; BRUBAKER et al., 1993). These changes affect the productive power of soils (STONE et al., 1985; WILLIAMS et al., 1984). Nevertheless, no general conclusions have been drawn about the size of changes for these soil parameters, as this kind of empirical study takes place under differing environmental conditions.

We wanted to understand how soil erosion influences various soil parameters and how it affects soil productivity under local conditions. In particular, we were interested in how soil physical and chemical parameters at eroded sites affected crop yields. We therefore selected a typical slope located within the prealpine zone of the Austrian molassic basin and studied the various physical and chemical soil parameters as well as crop yields at four different positions along the slope.

Zusammenfassung

Bodenerosion stellt einen entscheidenden Prozess für die Bodenbildung auf Hängen dar. Die Wechselwirkung von Erosion und Deposition beeinflußt verschiedene Bodeneigenschaften und Bodenfunktionen. Um diese Effekte zu quantifizieren, haben wir bodenchemische und bodenphysikalische Parameter, sowie Erträge an vier Erosionsstadien entlang eines Hangtransekts in der niederösterreichischen Molassezone untersucht. Eine Auswirkung der Hangposition konnte für bodenchemische Parameter vor allem im Ap Horizont festgestellt werden, während Unterschiede in tiefer gelegenen Horizonten im Allgemeinen gering waren. Veränderungen der Bodentextur, Feldkapazität und permanenter Welkepunkt waren vorhanden, aber gering. Die Ertragsänderungen variierten während des Untersuchungszeitraumes (1996–1999) und waren hauptsächlich der geringeren nutzbaren Feldkapazität des effektiven Wurzelraumes der erodierten Hangpositionen zuzuschreiben.

Schlagworte: Bodenerosion, Bodenproduktivität, chemische Bodeneigenschaften, physikalische Bodeneigenschaften.

Summary

Soil erosion is a major part of the process of soil formation at the hillslope scale. The interaction of erosion and deposition may change various soil properties and functions. To evaluate these effects we studied the change in various chemical and physical soil parameters, as well as associated crop yields, in four different sections of a slope in the molassic area of Lower Austria. We observed changes in soil chemical parameters mainly for the Ap horizons of the different slope sections, whereas changes in the deeper horizons were small. Changes in soil texture and field capacity were observed, although they were small. Yield reductions at the more eroded sections of the site varied during the study period and were mainly attributable to differences in the water holding capacity of the effective rootable zone of the different sections.

Keywords: soil erosion, soil productivity, chemical soil properties, physical soil properties.

2. Materials and Methods

The study area is located at the valley borders of the river "Große Erlauf" near the town of Wieselburg (Fig. 1). The soils were formed from calcareous clayey-sandy molassic sediments. The climate is characterized by annual rainfall of 724 mm, a mean annual temperature of 8.2° C and 223 days with more than 5° C (BMLF, 1996). For the purposes of the experiment the slope was divided into four sections I, II, III and IV (Fig. 1), located at different geomorphological positions – shoulder, upper linear, lower linear and footslope (BRUBAKER et al., 1993). At each section a detailed pedological description was made and various chemical and physical soil characteristics and plant yields were determined at intervals during a three-year period.

Soil types were classified according to the Austrian soil classification system (NESTROY et al., 2000) and the FAO (1998) system.

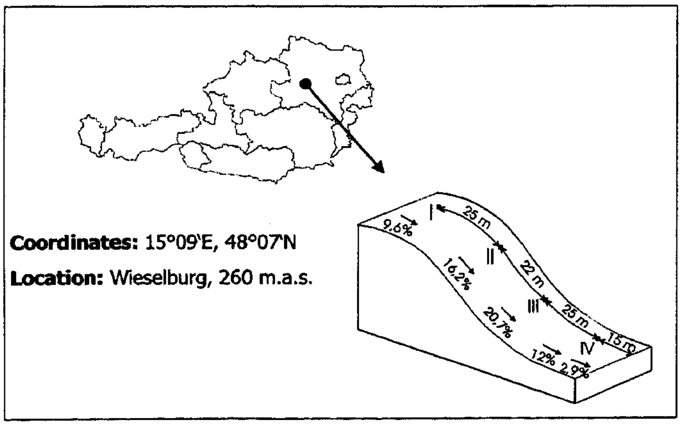

Figure 1: Location and general characteristics of the site studied
Abbildung 1: Lage und allgemeine Charakteristika des Untersuchungsgebietes

Soil chemical analysis consisted of pH (in $CaCl_2$), $CaCO_3$ (Scheibler method), organic carbon (organic C, wet combustion), total nitrogen (N_t – Kjehldahl method), total phosphorus (P_t – digestion with aqua regia and subsequent photometric determination), plant available phosphorus and potassium (P_{Cal}, K_{Cal} – extraction with calcium-acetate-lactate, analysis using ICP), potential cation exchange capacity (CEC, using $BaCl_2$ as extractant) and exchangeable cations Ca, Mg, K, Na (using $BaCl_2$ as extractant). Results are presented as the means of at least two independent samples from each of two different years.

Soil physical analysis consisted of particle size distribution (pipette method), bulk density (using 200 cm^3 cylinders), and water retention characteristics (pressure plates). To measure soil moisture and temperature regimes at the sites, gypsum blocks and temperature sensors were installed at the depths of 5, 10, 25, and 40 cm for section I; 5, 10, 25, 50, and 100 cm for sections II and III; and 5, 10, 25, 50, 100 and 150 cm for section IV (STENITZER, 1993). Readings were made weekly during the growing season of two consecutive years. Results are presented as the means of at least five independent samples.

All physical and chemical methods are described and referenced in BLUM et al. (1996).

Yield determinations at each section were made for the years 1996, 1998 and 1999. In 1997 no tests were carried out due to lack of manpower. During these years winter wheat (1996, 1999) and maize (1998) were grown. For winter wheat three plots of 1 m^2 were collected at each section. For maize three plots with two plant rows 1 m in length were collected at each section. For 1996 only grain yield was determined; for 1998 and 1999 grain yield and biomass yield were determined.

3. Results

3.1 Pedological description

The pedological description reveals a typical catena of soil types, from a highly eroded A-C type of soil profile at section I (Regosol) to Cambisols with varying depth of B horizons (at sections II, III) and ending with an Anthrosol (at section IV), highly influenced by deposition of material which had been eroded upslope (Table 1a–d). The main differences of Munsell soil colour for the A horizons of the different sections appear between section I and sections II, III and IV, where the latter exhibit lower values as well as chromas. This can be attributed to the lower content of organic matter for the Ap horizon of section I compared to sections II, III and IV (Fig. 2).

Another indication of the influence of soil erosion on the development of the soil profiles is the depth at which soil colour changes appear within each site. While for site II colour changes from 10 YR 4/2 to 10YR 5/6 at a depth of 40 cm, a similar change in colour happens at 50 cm for site III and at 95 cm at site IV.

3.2 Soil chemical parameters

As the biggest changes in soil chemical parameters were observed for the Ap horizons of the sections, we will mainly focus on changes within this horizon. For a more detailed description of the chemical properties in deeper horizons of the sections see STRAUSS et al. (2001).

Organic carbon contents (Fig. 2) steadily increased from section I (1.0%) to section IV(1.4 %). This corresponds to a relative increase of 40%. A similar trend was observed for P_{Cal} (Fig. 2) which increased about 60 % between section I and IV. According to the Austrian recommendations of good agricultural practice (BMLF, 1999) sections I and II would belong to fertilizer requirement group C (sufficiently supplied), while sections III and IV already belong to group D (well supplied). Following these recommendations different fertilization schemes should be applied at different positions on the slope.

K_{Cal} contents (Fig. 2) decreased from section I to III, then increased again at section IV to reach a similar level as at section I. As with P_{cal} contents, different fertilization schemes should be applied for sections I, II and IV (fertilizer requirement group D) compared to section III (fertilizer requirement group C).

In contrast to plant available phosphorus concentrations, total P contents did not change much along the investigated slope (Fig. 3). A decrease of total P contents could, however, be observed, from section I to section IV. Total nitrogen of the respective Ap horizons exhibited the smallest changes, rising from 0.14 % at section I to 0.16 % at section IV (Fig. 3). pH values of the Ap horizons decreased steadily from section I to IV (Fig. 3). On this slope, soil is formed by calcareous material. As surface material is transported downslope, calcium-rich material reaches the surface. This effect is illustrated in Figure 4, which shows the content of $CaCO_3$ at different depths in the soil profiles. While for section I, high amounts of $CaCO_3$ could be measured at depths of 5 cm, similar values for $CaCO_3$ were detected at depths of 100 cm for sections II and III. At section IV no $CaCO_3$ was found until a depth

Abschnitte I bis IV.

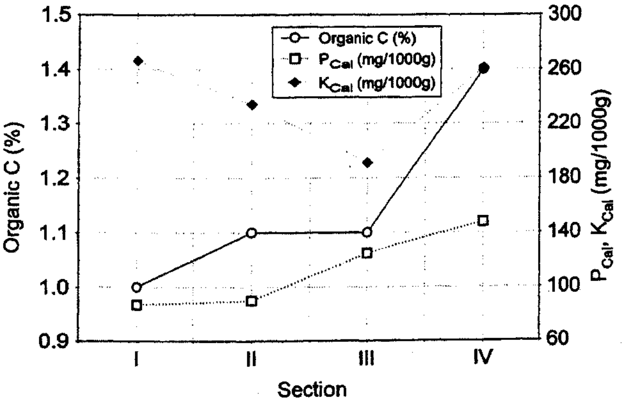

Figure 2: Contents of organic C, P_{Cal}, K_{Cal} for the Ap horizons of sections I to IV

Abbildung 2: Gehalte an organischem Kohlenstoff, P_{Cal}, K_{Cal} des Ap-Horizonts für die Abschnitte I bis IV

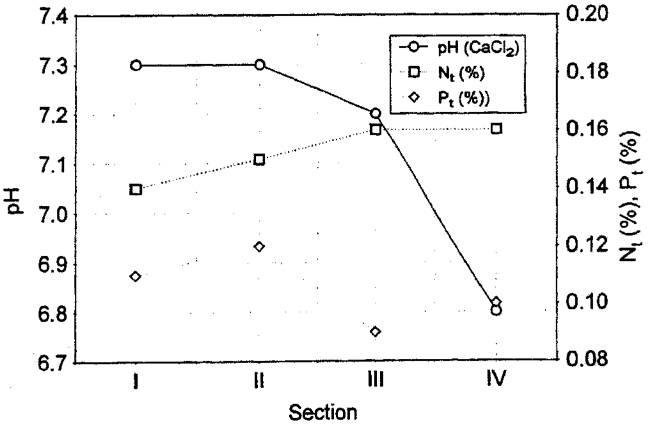

Figure 3: Contents of N_t and P_t and pH values for Ap horizons of sections I to IV

Abbildung 3: Gehalte an N_t und P_t sowie pH-Werte des Ap-Horizonts der Abschnitte I bis IV

Table 1: Pedological description of soil profiles at sections I, II, III and IV (depths in cm)
Tabelle 1: Beschreibung der Bodenprofile in den Abschnitten I, II, III und IV (Tiefenangaben in cm)

Section A:
Austrian classification system: carbonathaltiger Kulturrohboden
FAO: Calcari-anthropic Regosol

Horizon	Depth	Description
A_p	– 25	Sandy loam, 10 YR 5/3, clear boundaries, common roots
C_1	– 45	Sandy loam, 10 YR 6/3, clear boundaries, common roots, indistinct singular ribbons of weathered spots, ribbons of limestone, calcareous spots
C_2	45 +	Weathered sand-limestone, platelike structure, no roots

Section B:
Austrian classification system: carbonathaltige Braunerde
FAO: Endoskeletic Calcisol

Horizon	Depth	Description
A_p	– 25	Sandy loam, 10YR 4/2, many roots, clear boundaries, common mottles (Mn, Ø 1 mm), few coarse fragments and stones
B_v	– 40	Loam, 10YR 5/6, many roots, diffuse boundaries, many mottles (Mn, Ø 1 mm), few coarse fragments and stones
C_1	– 60	Loamy silt, 10YR 5/4, common roots, diffuse boundaries, few mottles (Mn, Ø 1 mm) many indistinct weathered spots (round), calcareous ribbons, few coarse fragments and stones
C_2	– 95	Loamy sand, 10YR 5/8, no roots, diffuse boundaries, calcareous ribbons, sandstones, many coarse fragments and stones
C_3	95 +	Sandy silt, 2.5 YR 5/4, no roots, many indistinct weathered spots (ribbonlike), calcareous ribbons, few coarse fragments and stones

Section C:
Austrian classification system: pseudovergleyte carbonathaltige Braunerde
FAO: Stagni-calcaric Cambisol

Horizon	Depth	Description
A_p	– 25	Loam, 10 YR 4/2, diffuse boundaries, common roots, few mottles (Mn, Ø 1 mm)
AB_v	– 50	Loam, 10 YR 4/3, diffuse boundaries, common roots, many mottles (Mn, Ø 1 mm)
B_{vg}	– 75	Loam, 10 YR 5/6, clear boundaries, common roots, many mottles (Mn, Ø 1 mm), few indistinct mottles (Fe), few weathered sandstones (Ø 5-10 cm)
C_1	– 95	Sandy loam, 2.5 YR 5/4, clear boundaries, no roots, many coarse fragments (platelike), ribbonlike weathered spots
C_2	– 160	loamy sand, 2.5 YR 5/3, clear boundaries, few indistinct ribbonlike weathered spots, ribbon of sandstone at 140 cm, calcareous ribbons
C_3	160 +	weathered calcareous sandstone

Section D:
Austrian classification system: vergleyter carbonathaltiger Kolluvisol
FAO: Calcari-terric Anthrosol (endogleyic)

Horizon	Depth	Description
A_p	– 30	Sandy loam, 10 YR 4/2, diffuse boundaries common roots, few mottles (Mn, Ø 1 mm)
AB_{1v}	– 95	Loamy silt, 10 YR 4/3, diffuse boundaries, common roots, many mottles (Mn, Ø 1 mm)
AB_{2g}	– 130	Loamy silt, 10 YR 5/3, diffuse boundaries, few roots, many mottles (Mn, Ø 1 mm), few indistinct mottles (Fe, Ø 1mm), few indistinct mottles (Fe gleyic, Ø >1 mm)
BG	– 195	Loam, 10 YR 5/4, abrupt boundaries, no roots, many mottles (Mn, Ø 2 mm), few indistinct mottles (Fe, Ø >1 mm), few indistinct mottles (Fe gleyic, Ø >1 mm), few completely weathered sandstones
CG	195 +	Sandy loam, 2.5 YR 6/3, few mottles (Mn, Ø 1 mm), few distinct mottles (Fe, Ø >1 mm), many indistinct mottles (Fe gleyic, Ø >1 mm), few cemented Fe mottles (Ø 1 mm), platelike sandstones

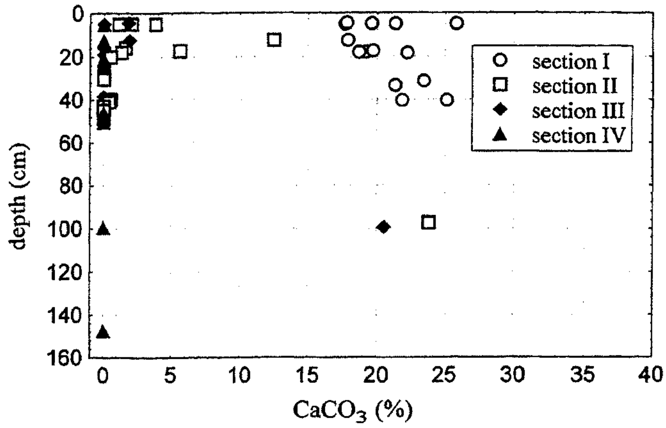

Figure 4: Contents of $CaCO_3$ for various depths of sections I to IV
Abbildung 4: $CaCO_3$ Gehalte der Abschnitte I bis IV in unterschiedlichen Tiefenstufen

of 150 cm. The existence of Ca^{2+} also determines cation exchange capacity (CEC) at the site. As a result of the increase in Ca^{2+}, CEC increased from section I to III from 158 to 192 $mmol_c/kg$, Ca^{2+} accounting for 92 % and 95 % respectively of total CEC. Due to a reduction of Ca^{2+} at section IV, CEC decreased to 158 $mmol_c/kg$ with Ca^{2+} accounting for 87% of total CEC. By contrast, the contribution of Mg^{2+} to CEC increased steadily from section I (7 $mmol_c/kg$) to IV (18 $mmol_c/kg$).

3.3 Soil physical parameters

Selected physical properties of the different sections are given in table 2. Selective transport has tended to accumulate finer material in the Ap horizons of the lower slope sections, as also observed by BRUBAKER et al. (1993) and LOWERY et al. (1995). Effects in deeper horizons were partially masked by the geogenic background of the sections. Together with organic matter content, this accumulation accounts for the observed differences in field capacity and wilting point at the different sections and horizons. Changes in the Ap horizons of sections I to IV are small, however. The main difference in the physical properties of the sections may be found in the total amount of available water. The pedological description reveals that the depth to which plant roots may grow without restriction (depth to an unfavourable horizon) increases from section I to section IV, with values of 45, 60, 75 and 130 cm respectively. This explains the strong increase in the total amount of plant available water capacity (Table 2). Compared to section I, the amount of plant available water increases by more than 100% in section IV. This may affect plant productivity in years with low amounts of available water. In fact, monitoring the results of water suctions at various depths using gypsum blocks (Figure 5) demonstrated that water depletion rates were quite different for the various sections and years.

Table 2: Soil physical characteristics for the effective rootable zone of sections I to IV. Fc = water content at 100 hPa, Wp = water content at 1500 hPa, Wc = available water capacity of respective horizon, Total = available water capacity of effective rootable zone, Bd = Bulk density of horizon
Tabelle 2: Bodenphysikalische Charakteristika der effektiven durchwurzelbaren Bodentiefe der Abschnitte I bis IV. Fc =Wassergehalt bei 100 hPa, Wp = Wassergehalt bei 1500 hPa, Wc = nutzbare Feldkapazität des Horizonts, Total = nutzbare Feldkapazität des effektiven durchwurzelbaren Raums, Bd = Trockenraumdichte des Horizonts

section	horizon	depth cm	sand (%)	silt (%)	clay (%)	Fc Vol. %	Wp Vol. %	Wc mm	Bd g/cm³
I	A_p	0–25	34	47	19	38.1	17.0	52.8	1.45
I	C_l	25–45	36	47	19	30.8	8.3	45.0	1.56
							Total	**97.8**	
II	A_p	0–25	31	45	24	40.9	20.4	51.3	1.48
II	B_v	25–40	21	41	38	45.1	24.3	31.2	1.47
II	C_l	40–60	25	57	18	36.3	10.4	51.8	1.48
							Total	**134.3**	
III	A_p	0–25	25	48	27	39.7	22.6	41.5	1.60
III	AB_v	25–50	21	45	34	37.3	23.2	35.3	1.44
III	B_{vg}	50–75	16	46	38	37.5	20.6	42.3	1.52
							Total	**119.1**	
IV	A_p	0–30	25	50	25	39.3	19.5	59.4	1.50
IV	AB_{1v}	30–95	24	56	20	32.0	15.6	106.6	1.57
IV	AB_{2g}	95–130	20	56	24	33.3	18.3	52.5	1.57
							Total	**218.5**	

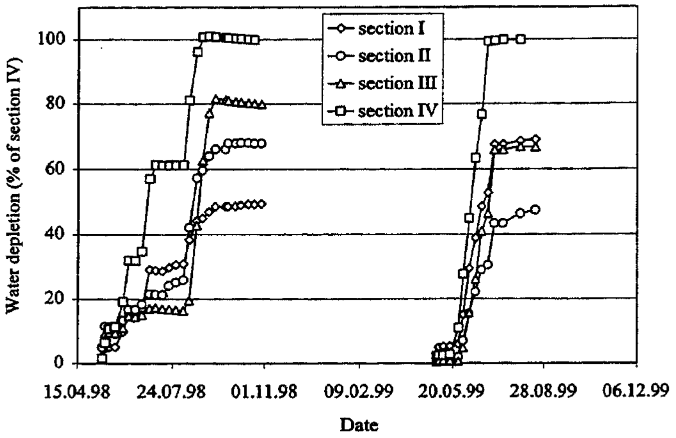

Figure 5: Accumulated water depletion for two consecutive years of sections I to IV, as a percentage of water depletion at section IV

Abbildung 5: Akkumulierter Wasserentzug zweier Jahre für die Abschnitte I bis IV, in Prozent des Wasserentzugs von Abschnitt IV

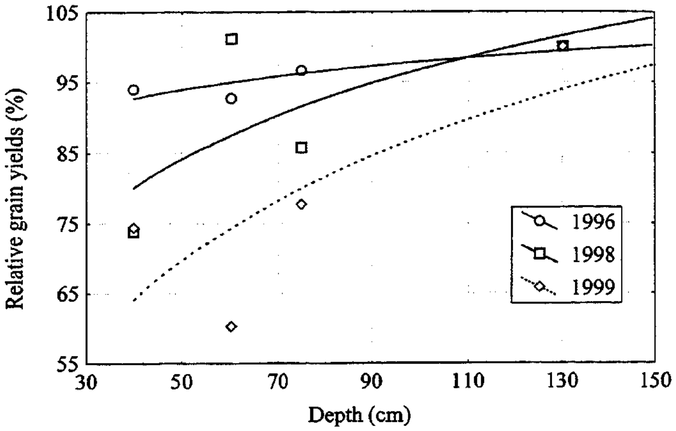

Figure 6: Relative grain yields (as % of yield of section IV) for years 1996, 1998, 1999 compared to the respective depths to an unfavourable horizon of sections I to IV

Abbildung 6: Relative Kornerträge (in % des Kornertrags von Abschnitt I) der Jahre 1996, 1998, 1999 im Verhältnis zur durchwurzelbaren Tiefe der Abshnitte I bis IV

3.4 Yields

Due to the lack of available data the depth to an unfavourable horizon has commonly been used as a surrogate for an evaluation of the effect of soil erosion on soil productivity (CHRISTENSEN and MCELYEA, 1988; RHOTON and LINDBO, 1997). After a review of the available literature on the topic, STOCKING and PEAKE (1985) found a curvilinear, exponentially shaped relationship between amount of soil erosion (depth to an unfavourable horizon) and soil productivity decline. Due to the limited data set of four sections and three years we do not feel it appropriate to explicitly corroborate or reject this model. In our study, grain yields were generally higher at section IV (630 g/m^2 in 1996, 84 g/plant in1998, and 641 g/m^2 in 1999) compared to the other sections. Similar results were obtained for biomass weights. To make the results from the different years more easily comparable we calculated relative grain yields, i.e. the yields at section I, II and III were expressed as a percentage of yield at section IV. We then plotted these results against depth to an unfavourable horizon (Fig. 6). With the exception of the results for section II in 1999 which exhibited strong deviations, relative grain yields increased from section I to IV. The reason for the strong deviations in section II in 1999 could not be detected but one indication that results are not due to measurement errors is that similar deviations in water depletion were identified at section II in 1999 (Fig. 5). A comparison of the slopes of the regression lines in Figure 6 indicates that the relationships between yield and geomorphological position is highly variable. A comparison of 1996 and 1999 (winter wheat was grown in both years) reveals that the effect of slope position on yields was much stronger in 1999. Records of rainfall and potential evapotranspiration for the site show that for April – July 1999, only 299 mm of rainfall fell compared to 426 mm in 1996. In addition, potential evapotranspiration for these months was about 45 mm higher in 1999 than in 1996. Given the good status of fertilization in the Ap horizon of each of the sections and the relatively small differences in deeper horizons, it can be concluded that the climatological situation and its impact on water supply was the main cause of yield reduction in 1999. This is also supported by the results for water depletion rates in these sections in 1996 and 1999 (Fig. 5).

4. Conclusions

Evaluation of soil chemical and physical properties at the study site revealed that soil erosion affects almost all soil parameters, though the extent to which the various soil parameters were affected varied considerably. Changes in chemical parameters were mainly observed in the Ap horizons of the different sections. The differences in water availability are not so much the result of big differences in soil physical parameters but can be attributed to the differences in storage amounts of plant available water. It was not possible to establish numerical relationships between soil erosion and soil productivity, as to do this it would be necessary either to run long-term experiments, or to use hydrological simulation models because the availability of water at the different sections was a main source of yield reduction. This latter finding is significant as the study area is not located in a region with low rainfall and low water availability for plant production is not normally considered a problem.

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