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Effects of land use on structure and hydraulic properties of Vertisols containing a sodic horizon in northern Ethiopia

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ABSTRACT

In recent decades significant clearing of native *Acacia seyal* and *Balanites aegyptiaca* savannah has preceded expansion of agricultural lands in the semiarid Sahel regions of northern Ethiopia. The main objective of this study was to determine the effects of changes in land uses on structure and saturated hydraulic conductivity (K_s) of a Vertisol under sodic conditions. Disturbed soil samples were taken from savannah-woodland landscape and from cultivated sorghum and sesame fields in the Humera region of Ethiopia, for determination of chemical properties, aggregate stability and K_s. Exchangeable sodium percentage (ESP) increased with soil depth, from ~2% in the 0–0.15 m layer to 8.1–10.6% in the 0.9–1.2 m layer. Swelling and dispersion was more pronounced in the subsoil (0.9–1.2 m) than in the topsoil of the three land uses, due to the higher ESP values of the former. In contrast, the topsoil was more sensitive to slaking forces than the subsoil, probably due to increased particle cohesion in the subsoil. This led to lower K_s values of the topsoils under fast than slow prewetting. The steady-state K_s values under slow prewetting and leaching with deionized water were significantly higher in the savannah-woodland soil than in the cultivated soils, down to 1.2 m depth. These differences in K_s values were associated with higher swelling values in the cultivated soils than in the savannah-woodland soil. The differences in the swelling values were manifested at the field scale, where the cracking in the cultivated soils was more intense than in the savannah soil. It was suggested that conversion of natural savannah vegetation to cultivated crops and tillage operations destabilized soil structure in the cultivated plots mainly by an increase of the swelling forces, which, in turn, reduced the K_s values.

1. Introduction

In recent decades, African grassland, woodland, and other virgin lands have increasingly been converted into cropland. For instance, an estimated 3.4 million km^2 of woody vegetation in arid and semiarid zones of Africa have become degraded through anthropogenic activities, such as agricultural expansion and deforestation (Tsegaye et al., 2010). One such area subjected to human-induced land use changes is the Humera district, located in a lowland region of Tigray, Ethiopia (Fig. 1). The economy of this district is based on sesame seed production for export, which employs 350,000–500,000 seasonal workers annually. Additionally, in 2003, the Humera region was selected by the Ethiopian authorities as an area for voluntary resettlement of farmers from overpopulated areas. As of 2007, about 16,000 households were resettled in the Humera district (DRMFSS, 2007). The influx of resettled populations and seasonal workers, combined with semi mechanized sesame production, are exerting increasing pressure on the area's diminishing natural resources. Consequently, significant clearing of the native *A. seyal*- and *B. aegyptiaca*-dominated savannah, and subsequent cultivation and grazing have taken place over the past few decades (Gebre-Michael et al., 2010) and, at present, very few areas of natural savannah remain in the region. This drastic shift in land use may seriously affect the chemical, physical, and hydraulic properties of the soil. Furthermore, it may also affect the abiotic conditions that support various soil-borne biota, e.g., the sand flies that act as vectors of the deadly kala-azar disease (Gebre-Michael et al., 2010), which poses a serious health threat in the Humera region.

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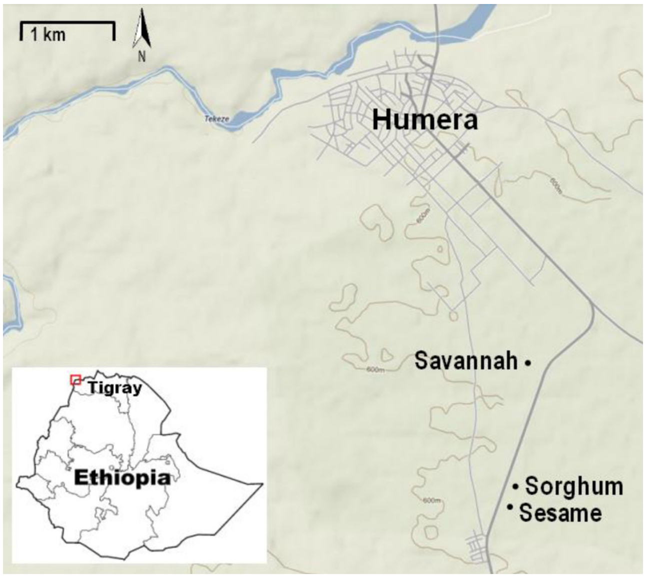

Fig. 1. Map of Ethiopia and study area.

The dominant soil in the Humera region is chromic Vertisol (Amare et al., 2009), characterized by high contents of smectitic clay minerals. Vertisols are strongly affected by moisture content: they swell when hydrated and shrink upon desiccation, causing extensive cracking during the dry season. Also, wetting of the soil may disperse clay particles. A clayey soil, such as a Vertisol, may therefore be highly sensitive to structure-altering processes under land use changes.

One property that is highly dependent on soil structure, and may, therefore, be affected, is hydraulic conductivity (K) (Bouma and Anderson, 1973; Hillel, 2004; Shainberg and Letey, 1984). Hydraulic conductivity of soil is an important parameter, which affects water and solute transport, and water availability for plants. In arid and semi-arid regions, where precipitation is scarce and unevenly distributed, the capacity of the soil to conduct and store water is crucial. For example, Kadu et al. (2003) evaluated the suitability of Vertisols in India for crop production, and found low crop yields in soils with low K values. Furthermore, reduced K values can lead to reduced infiltration and soil aeration and increased surface runoff and soil erosion (Ben-Hur, 2008; Ben-Hur and Lado, 2008; Kadu et al., 2003), with consequent alterations to the hydrological cycle, soil fertility, and soil biotic conditions.

Saturated hydraulic conductivity (K_s) is a function of pore-size distribution and tortuosity (Hillel, 2004), and also of aggregate stability (Ben-Hur et al., 2009). Clay particles in soil are associated to form aggregates and pores of various sizes by means of stabilizing agents, such as organic matter, calcium carbonate, and oxides (Bronick and Lal, 2005; Duiker et al., 2003; Gargiulo et al., 2013; Tisdall and Oades, 1982). In soil, the volume of water transmitted and the rate of transmission is greater for larger than smaller pores (Moutier et al., 1998). Lado et al. (2004) and Ben-Hur et al. (2009) found that an increase in organic matter content improved the stability of soil structure, which, in turn, augmented the soil K_s value. Deforestation and subsequent soil cultivation may reduce soil organic matter content (Collard and Zammit, 2006; Dalal and Mayer, 1986), because of reduction in organic residues added to the soil, destruction of macro-aggregates, and increased microbial oxidation of organic carbon (Whitbread et al., 1998). It was shown that, compared with native pasture or woodland soils, Vertisols used for crop production had a higher bulk density (Biro et al., 2011; McKenzie et al., 1991; Whitbread et al., 1998) and were more prone to dispersion (Cook et al., 1992; McKenzie et al., 1991; Whitbread et al., 1998). The reduction in soil organic matter content, alteration of soil porosity, soil compaction, and decline in aggregate stability could adversely affect soil K (Azooz and Arshad, 1996; Radford et al., 2000; Whitbread et al., 1998).

In the absence of raindrop impact and external compacting pressures, there are three main mechanisms that could degrade soil structure during wetting and leaching: (i) aggregate slaking; (ii) soil swelling; and (iii) clay dispersion (Ben-Hur et al., 2009). Aggregate slaking occurs when soil is wetted rapidly and its aggregates are not strong enough to withstand the stresses produced by differential swelling, pressure of entrapped air, rapid release of heat during wetting, and mechanical action of moving water (Emerson, 1977; Kay and Angers, 1999). These stresses are termed slaking forces, and their intensity is a function of the wetting rate of the soil; the faster the wetting the stronger the slaking forces and the greater the proportion of aggregates that undergo slaking.

Soil swelling is essentially a reversible process, in which the total volume of soil increases upon hydration; it depends mainly on the soil mineralogical, chemical, and physicochemical properties (Ben-Hur et al., 2009; Dasog et al., 1988; Greene-Kelly, 1974; Lado and Ben-Hur, 2004; Smith et al., 1985). Greater swelling is expected in soils with high contents of smectitic clay minerals, high exchangeable sodium percentage (ESP), and a low electrolyte concentration in the soil solution. Swelling of clay particles increases the content of small, water-retaining pores at the expense of larger water-conducting pores (Kutilek, 1996; Moutier et al., 1998).

Clay dispersion is an irreversible process, in which quasicrystals or domains (regions of parallel alignment of individual aluminosilicate lamellae in smectite minerals) break apart and disperse because of mutual-repulsion forces (van Olphen, 1977). Dispersion of soil clay occurs instantaneously once the electrolyte concentration of the soil solution falls below a threshold value, termed the flocculation value (Oster et al., 1980), and the dispersed clay particles may migrate and plug water-conducting pores, causing a reduction in soil K_s (Frenkel et al., 1978). Clay dispersion is influenced by soil chemistry and mineralogy, and is enhanced primarily by a low electrolyte concentration in the soil solution and high ESP of the soil (Lado et al., 2004; Laird, 2006; Malik et al., 1992; Oster et al., 1980). Thus, K_s tends to decrease as soil ESP increases and as the electrolyte concentration of the soil solution decreases (McNeal and Coleman, 1966; Quirk and Schofield, 1955).

Many studies have focused on the effects of sodicity and water quality on the structure and hydraulic properties of soils (e.g., Chaudhari, 2001; Frenkel et al., 1978; Gupta and Verma, 1984; Malik et al., 1992; Shainberg and Letey, 1984). The effects of tillage on soil structure and K have also been addressed (e.g., Bandyopadhyay et al., 2003; Hewitt and Dexter, 1980; Oicha et al., 2010; Radford et al., 2000; Whitbread et al., 1998). Other studies have mainly addressed the effects of changes in land use and of cultivation on soil chemical properties, such as organic matter and nutrients contents and cycling (Collard and Zammit, 2006; Dalal and Mayer, 1986; Solomon et al., 2002). In contrast, the effects of interactions between land use changes, on the one hand, and sodic conditions, on the other hand, on soil structure and K_s of Vertisols have not been well documented. Therefore, the aim of the present study was to examine the effects of changes in land use – from natural sparse forest (savannah-woodland) to semi mechanized crop production – on soil structure and K_s of a Vertisol, under sodic conditions in the Humera region of Ethiopia.

2. Materials and methods

2.1. Studied sites and soil sampling and analysis

The research was conducted in the Humera district of northwest Tigray, Ethiopia (Fig. 1). This region is situated in a semi-arid plain at an elevation of about 600 m above sea level. The average annual rainfall is 600 mm, falling primarily between June and September; the yearly average temperature is 29 °C, the mean monthly minimum/maximum air temperatures are 21 and 39 °C, respectively, and the annual potential evapotranspiration is 1770 mm. The soil is an alluvial, non-calcareous Vertisol.

Three plots in the Humera region were chosen to represent different land uses. The topography of the three land use plots was of a low relief plain. One plot was in a natural savannah landscape and the other two represented typical agricultural fields, used for sorghum (*Sorghum bicolor*) and sesame (*Sesamum indicum*), respectively. The savannah landscape (Fig. 2a) is dominated by *A. seyal* and *B. aegyptiaca* trees, and is categorized as *Acacia-Commiphora* woodland (NBSAP, 2005). The studied plot in the savannah land use was mostly undisturbed, used solely to provide shade for animals that graze on crop residues in the nearby agricultural fields. The location of soil sampling in the savannah plot was 14°15′42″ N, 36°37′24″ E. The two agricultural plots (Fig. 2b) were previously natural savannah that was converted to crop production a decade ago: one plot with monoculture sesame rotation; the second with sorghum/sesame rotation. Below we refer to the first plot as a sesame land use and the second plot as a sorghum land use. The cultivated plots were adjacent to one another, and not far – about 1500 m – from the savannah plot. The location of soil sampling in the agricultural plots was 14°14′46″ N, 36°37′06″ E. The agricultural fields were seeded manually on untilled soil after an effective rainfall event, and the seeds were covered by means of a single pass of a disk harrow carrying 24–30 discs (M. Amare, Humera Agricultural Research Center, personal communication, 2013). The plants were not fertilized or irrigated at any time, and the yield was harvested manually. Sometimes, weed control in these fields was carried out with a post-harvest pass with a disk harrow.

Disturbed soil samples were taken from the three study plots at the end of the dry season in 2010; each plot was sampled three times (three replicates) along a 50 m transect. Alluvial Vertisols are inherently homogenous vertically and horizontally, which was reaffirmed, at large, regarding the general chemical and physical properties of the soils (Table 1). Thus, the sampling scheme satisfactorily represented the study plots. At each sampling site a soil core was collected with an auger, down to a depth of 1.2 m, and the cores were divided into contiguous segments representing soil depths of 0–0.15, 0.15–0.3, 0.3–0.6, 0.6–0.9, and 0.9–1.2 m. The soil from each sampling segment was air dried, cleared of visible roots and organic residues, mixed for homogeneity, and stored pending chemical and physical analysis.

Crushed and sieved soil samples of aggregate size <2 mm were used to determine: the soil mechanical composition by the

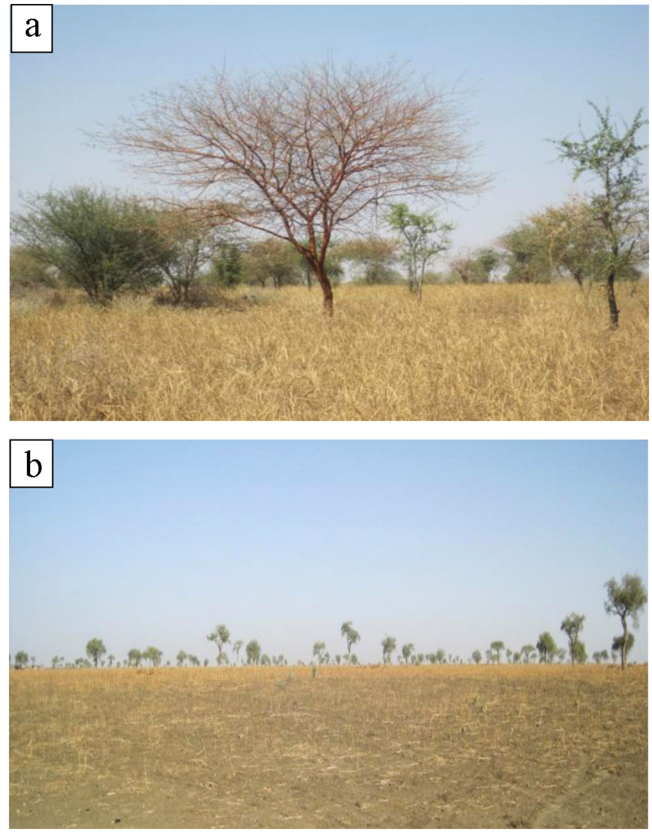

Fig. 2. Study sites in the Humera district of northern Ethiopia. (a) Savannah (b) Fallow sesame field.

Table 1
Mechanical composition, cation exchange capacity (CEC), and organic matter content (OM) in soil, and pH and electrical conductivity (EC) values in soil water extract for the studied soils and at various soil depths.

Soil depth (cm)	Mechanical composition			OM (%)	CEC (meq 100 g^{-1})	Soil water extract (1:2 soil:water)	
	Clay (%)	Silt (%)	Sand (%)			pH	EC (dS m^{-1})
Savannah							
0–15	66.6[a]	15.6	17.8[a]	1.68[a,b]	72.9	7.9	0.3[a]
15–30	64.8	19.7	15.6	1.39	71.8	7.7	0.3
30–60	66.9	15.5	17.6	1.33	71.5	7.8	0.3
60–90	68.6	15.5	15.9	1.31	70.4	8.0	0.4[a]
90–120	68.8	15.4	15.8[a]	1.23	74.0	8.4	0.5[b]
Sorghum							
0–15	71.2	15.5	13.4	1.33	78.3	7.8	0.2
15–30	70.9	14.2	14.9	1.31	78.3	7.6	0.2
30–60	70.8	14.3	14.9	1.35	83.2	7.6	0.3
60–90	69.6	14.8	15.6	1.29	79.8	7.7	0.3
90–120	72.1	17.4	10.5	1.22	81.6	8.0	0.4[a,b]
Sesame							
0–15	71.7	17.1	11.3	1.39	82.7	8.0	0.2
15–30	71.9	12.5	15.6	1.30	78.4	8.1	0.3
30–60	69.3	12.7	18.0	1.30	81.6	8.1	0.3
60–90	70.6	8.8[a,b]	20.6[a]	1.24	80.2	8.3	0.3
90–120	73.3	15.8	10.8	1.29	83.5	8.3	0.5[b]

[a] Indicates values that are significantly different among the land uses for each column and soil depth layer.
[b] Indicates values that are significantly different among the soil depths for each column and land use.

hydrometer method (Day, 1956); $CaCO_3$ content by the CO_2-release volumetric method (Allison and Moodie, 1965); organic matter content by the Walkeley-Black method (Allison, 1965); exchangeable sodium content and cation exchange capacity (CEC) by extraction with ammonium acetate at pH 7 (Chapman, 1965). For mineralogical analysis, carbonates and salts were removed with buffered acetic acid, the clay fraction was collected by means of ultrasonic treatment and sedimentation, and the clay mineralogy was determined by X-ray diffraction with a model Philips XRD (1730/1710). Mineralogical analysis was applied to soil samples from depths of 0–0.15 and 0.9–1.2 m in the savannah plot and in one agricultural field. The pH and electrical conductivity (EC) were determined in soil-water extract with a soil:water ratio of 1:2.

The soils were non-calcareous, and the major mineral in their clay fraction was smectite, dominated by interstratified illite–smectite. The soils had high clay contents and CEC levels – 65–73% and 70–83 meq 100 g^{-1}, respectively (Table 1), which are typical of Vertisols. The organic matter content was low, at 1.2–1.7%; pH was slightly alkaline, at 7.6–8.4, and salinity was low, at 0.2–0.5 dS m^{-1} (Table 1).

2.2. Saturated hydraulic conductivity

The K_s values of the soil samples were determined on disturbed soil columns by measuring flow rates under a constant hydraulic head that was controlled by a Mariotte bottle. For this measurement, each soil sample was crushed and sieved through a set of sieves with mesh sizes of 2.0, 1.0, 0.5, 0.25, and 0.1 mm, to obtain five different aggregate-size fractions. To ensure as uniform an aggregate distribution as possible in each of the soil columns, and to minimize the effect of non-uniformity on soil K_s (Lado et al., 2004), thoroughly blended mixtures of each soil were prepared; each mixture comprised 25, 31, 25, 13, and 6% (w/w) of aggregates in the size ranges: 1.0–2.0, 0.5–1.0, 0.25–0.5, 0.1–0.25, and <0.1 mm, respectively. A 0.12 kg aliquot of the blended mixture from each soil sample was packed on top of an approximately 1.0 cm layer of acid-washed sand inside a Plexiglas column with an inner diameter of 5 cm. The thickness of the test-soil layer in each dry column was about 4 cm and its bulk density was about 1.2 g cm^{-3}. A filter paper (Whatman No. 42) was placed on the top of the soil layer in each column to prevent mixing and turbulence when water was added.

All soil samples were initially wetted to saturation from beneath with saline water (SW) by means of a peristaltic pump, at a slow prewetting rate of 8.9 mm h^{-1}. This water had been prepared by dissolving NaCl and $CaCl_2$ in deionized water to obtain an electrolyte concentration of 50 mmol L^{-1} and a sodium adsorption ratio (SAR) values similar to the ESP of the soil being examined. Additionally, soil samples from the 0 to 0.15 and 0.9 to 1.2 m layers in the three land use plots were wetted from beneath with SW at a fast prewetting rate of 70 mm h^{-1}. After the soils were saturated, the columns were leached from above with three to four pore volumes of SW followed by deionized water until steady state, or close to it, was achieved with respect to the EC of the out flowing solution (leachate) and to the K_s of the soil. Deionized water was used for leaching because it is similar to rainwater in its electrolyte concentration. The leachate was collected continuously with a fraction collector during timed intervals, and its volume, EC and optical density were measured. The optical density (absorbance at 420 nm) and EC of the leachates were measured with a spectrophotometer and an EC meter, respectively. The K_s values were calculated by using Darcy's Law. The concentration of dispersed clay was calculated by reference to a calibration curve of absorbance value vs. suspended clay concentration, which had been previously prepared for each depth and land use.

2.3. Aggregate stability

Aggregate stability of the soil samples from the various soil depths in the three land uses was determined by using the slaking, swelling, and dispersion tests according to Ben-Hur et al. (2009), as briefly described below.

2.3.1. Slaking test

Soil samples from the 0 to 0.15 m (topsoil) and 0.9 to 1.2 m (subsoil) layers of each land use were subjected to both fast and slow wetting. For fast wetting, 5 g of oven-dried (40 °C) aggregates in the 2–4 mm size range were placed in a beaker containing 50 mL of deionized water. After 10 min, the water was carefully removed from the beaker with a pipette. The soil fragments were then transferred to a 50 μm sieve immersed in ethanol in a large plastic container, and the sieve was gently lowered and raised five times to separate <50 μm fragments from larger ones. The >50 μm fraction was oven dried, and then gently sieved by hand through a series of sieves of mesh sizes 2.0, 1.0, 0.5, 0.25, and 0.1 mm. The oven-dried weight of each fraction was measured and the <50 μm fraction was calculated as the difference between the initial sample weight and the sum of the weights of the remaining six fractions. The aggregate size distribution of each soil sample was expressed in terms of the mean weight diameter (MWD), which was calculated by using Eq. (1):

$$\text{MWD} = \sum_{i=1}^{7} \bar{x}_i w_i \tag{1}$$

where, w_i is the weight fraction of aggregates in the size class i with a mean diameter x_i.

For slow wetting, 5 g of oven-dried (40 °C) aggregates in the 2–4 mm size range were placed on a filter paper (Whatman No. 42), which was then placed in a desiccator, on a cotton cloth whose edges were immersed in deionized water, to allow the aggregates to moisten slowly under vacuum for 24 h. The wet aggregates were then transferred to a 50 μm sieve immersed in ethanol, oven-dried and sieved as described above for the fast wetting procedure. The MWDs of the slow-wetted aggregates were calculated with Eq. (1). The slaking value (SLV) of each soil sample was calculated with Eq. (2):

$$\text{SLV} = \frac{\text{MWD}_s}{\text{MWD}_f} \tag{2}$$

in which MWD_s and MWD_f are the mean weight diameters under slow and fast wetting, respectively.

2.3.2. Swelling test

From each soil sample, 20 oven-dried (40 °C) aggregates in the 2–4 mm size range were placed on filter paper (Whatman No. 42) and scanned with a tabletop scanner (Deskjet 4670, Hewlett-Packard). Their image areas were measured with UTHSCSA Image Tool Software (University of Texas Health Science Center, San Antonio, TX, USA). The aggregates were assumed to be spherical and their volumes were calculated from the geometry of circles with projected areas equal to those of the scanned aggregates. The aggregates on the filter papers were then wetted slowly, as described above for the slaking test and the swelling values (SWVs) of the soil sample were determined by using Eq. (3):

$$\text{SWV} = \frac{\sum_{i=1}^{n} \frac{(I_{wi} - I_{di})}{I_{di}}}{n} \tag{3}$$

in which, n is the number of aggregates, I_{wi} is the calculated volume of aggregate i after wetting, and I_{di} is the calculated volume of the dry aggregate i.

For all the soil samples, SWV was determined after slow wetting with deionized water. In addition, the SWVs of soil samples from the 0 to 0.15 m and 0.9 to 1.2 m layers in each of the three land uses were determined after slow wetting with SW.

2.3.3. Dispersion test

A 2 g aliquot of soil from each sample was suspended in 40 mL of deionized water in a 50 mL centrifuge tube, which was then shaken on a reciprocal shaker for 30 min at 20 rpm, and immediately centrifuged at 960 $\times$ g for 5 min. The absorbance at 420 nm and the EC of the turbid supernatant were measured with a spectrophotometer and an EC meter, respectively. The concentration of dispersed clay was calculated as described above (Section 2.2) for the saturated hydraulic conductivity. The dispersion value (DV) for each soil sample was determined by using Eq. (4):

$$\mathrm{DV} = \frac{M_d}{M_t} \times 100 \quad (4)$$

in which M_d is the mass of dispersed clay in the turbid supernatant per 1 g of tested soil sample, and M_t is the total mass of clay in 1 g of tested soil sample.

2.4. Statistical analysis

All experiments were conducted in three replicates. Means were subjected to one-way ANOVA, except for the between-land-uses comparison of saturated hydraulic conductivity and dispersion values, which were subjected to one-way ANOVA with ESP as a covariate. To account for the fact that five different soil samples from five different depths were taken at each of the three sampling points in each land use, the mixed model, a hierarchical model design, was used. Whenever a significant difference was found between land uses, the pair-wise comparison between the land uses was adjusted for multiple comparisons. Separation between means was subjected to Tukey's Honestly Significant Difference test. All tests were performed at $p = 0.05$.

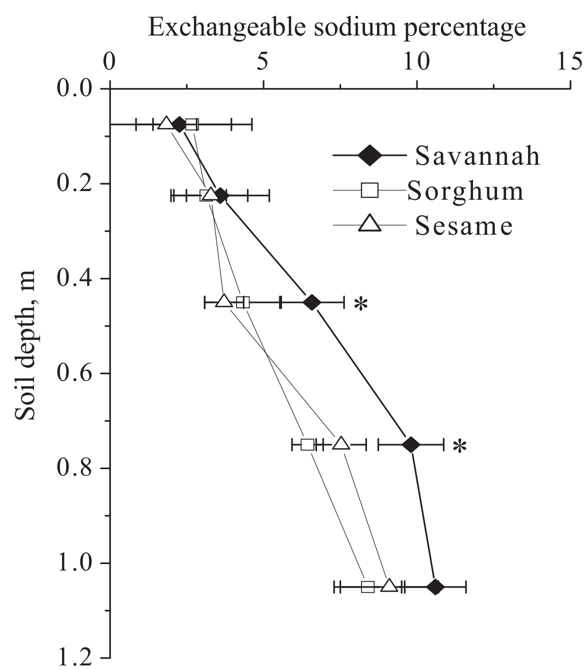

Fig. 3. Exchangeable sodium percentage as a function of soil depth for different land uses. Bars indicate two standard deviations. *Indicates significant differences between savannah and cultivated soils in a specific soil depth.

3. Results and discussion

Exchangeable sodium percentages for the various land uses (savannah, sorghum, and sesame) are presented in Fig. 3, as functions of soil depth. In all three land uses the ESP of the soil increased with depth, from an average of about 2% in the 0–0.15 m layer to values ranging from 8.4 to 10.6% in the 0.9–1.2 m layer (Fig. 3). Similar findings were reported in Vertisols under semi-arid conditions in India (Balpande et al., 1996) and in Israel (Singer, 2007). The increase in ESP with soil depth was probably a result of weathering of primary minerals containing Na, Ca, and Mg, deposition of salts on the soil surface by rainwater and æolian dust, and immigration and accumulation of Na in deep soil layers because of its higher solubility and mobility than Ca and Mg (Balpande et al., 1996; Singer, 2007). The ESP values at a depth >0.3 m were higher in the savannah than in the sorghum and sesame fields (Fig. 3), probably because: (i) there was more available Na in the savannah soil than in the others due to greater trapping of Na-containing dust by the canopy of the savannah vegetation than the canopy of the sorghum and sesame (Fearnehough et al., 1998); and (ii) differing hydraulic properties of the soils under the various land uses altered leaching and upward movement of salts, which in turn, changed the Na distribution in the soil profiles of the different land uses.

The K_s values of soil samples from the topsoil (0–0.15 m) and subsoil (0.9–1.2 m) of the three land uses, after being subjected to either slow or fast prewetting and leaching with SW, are presented in Fig. 4 as functions of cumulative leachate volume. In this case, the high electrolyte concentration of 50 meq L^{-1} in the leaching solution prevented clay dispersion (Keren and Ben-Hur, 2003). Therefore, the changes in the K_s values were mainly caused by slaking and swelling forces that altered the soil structure. The K_s values of the two soil layers (topsoil and subsoil) in the three land uses under the two prewetting rates were quite constant throughout the leaching run, and there were no significant differences in their values between land uses for each soil depth and prewetting rate combination (Fig. 4). But, the effects of slaking and swelling forces on soil structure and K_s values differed among the various land uses and soil depths. The K_s values of the soil in the three land uses and following prewetting at both rates were higher in the topsoil, where the average values were 133–363 mm h^{-1} (Fig. 4a and b), than in the subsoil layer where the average values were 36–117 mm h^{-1} (Fig. 4c and d). The highest average K_s value

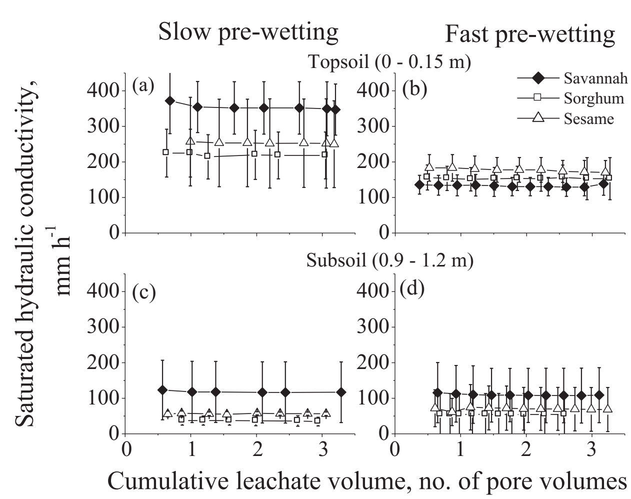

Fig. 4. Saturated hydraulic conductivity values of topsoil and subsoil from the various land uses under saline-water leaching following either slow or fast prewetting, as functions of cumulative leachate volume. Bars indicate two standard deviations.

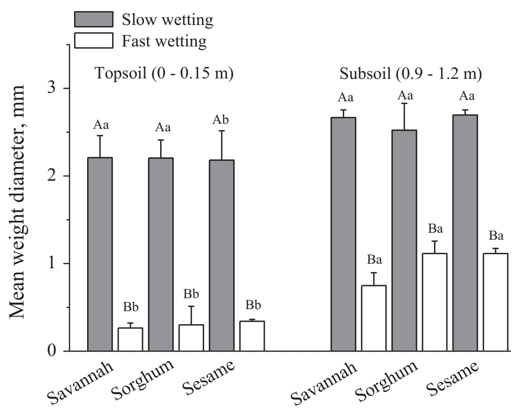

Fig. 5. Mean weight diameter (MWD) of topsoil and subsoil of the various land uses after slow and fast wetting. Bars indicate one standard deviation. Different uppercase and lowercase letters at the top of the columns indicate significant differences between wetting rates for each land use and soil layer, and between soil layers for each land use and wetting rate, respectively.

(363 mm h^{-1}) was found in the topsoil layer of the savannah soil under slow prewetting (Fig. 4a), and the lowest (36 mm h^{-1}) was in the subsoil layer of the sorghum soil under slow prewetting (Fig. 4c). In the topsoil, the average K_s values of the soils from the three land uses following slow prewetting were higher than those following fast prewetting: 220–363 and 133–177 mm h^{-1}, respectively. The largest difference was found in the savannah soil and the smallest in the sorghum (Fig. 4a and b). In contrast, in the subsoil, the differences in the K_s values between the slow and fast prewetting were small and insignificant (Fig. 4c and d).

The MWD values of the soil samples from the topsoil and subsoil layers of the three land uses after slow and fast wetting are presented in Fig. 5. The MWD values of the aggregates of the two layers and the three land uses were much higher under slow than under fast wetting (Fig. 5), and their slaking values were relatively high: >2.3 (Table 2). A slaking value of 1 would indicate that the effect of slaking forces on aggregate disintegration was negligible, whereas for slaking values >1 the higher the slaking value, the greater the role of the slaking forces in aggregate disintegration. The high slaking values (>2.3) of the studied soils (Table 2), which had clay contents >64.8%, are consistent with the results obtained by Lado et al. (2004) and Ben-Hur and Lado (2008), who found significant increases in slaking values as clay content increased. In the present study, the slaking values of the soils in the three land uses were significantly higher in the topsoil than in the subsoil layer: 6.4–8.7 and 2.3–3.8, respectively (Table 2). The aggregates in the 0.9–1.2 m soil layer were subjected to high compaction because of overburden pressure, and this probably increased the cohesion forces between the particles in the aggregates, leading to higher resistance to slaking forces. This can also be inferred from the higher MWD values of the aggregates from the subsoil than of those from the topsoil; these differences, although apparent under both slow and fast wetting, were statistically significant only under the latter (Fig. 5).

Table 2
Slaking values and swelling values of topsoil and subsoil in various land uses, after wetting with saline water (SW) or deionized water (DW). Different uppercase, lowercase, and italic letters indicate, respectively, significant differences between: land uses in the same soil layer and with the same water quality; soil layers in the same land use and with the same water quality; and water qualities in the same land use and soil layer.

Land use	Topsoil (0–0.15 m)			Subsoil (0.9–1.2 m)		
	Slaking value	Swelling value (%)		Slaking value	Swelling value (%)	
		SW	DW		SW	DW
Savannah	8.7Aa	51.6Ab*a*	54.6Bb*a*	3.8Ab	79.5Aa*b*	95.8Aa*a*
Sorghum	6.4Aa	71.5Ab*a*	79.9ABa*a*	2.3Ab	88.5Aa*a*	96.1Aa*a*
Sesame	7.4Aa	55.6Aa*b*	84.3Aa*a*	3.6Ab	75.4Aa*b*	92.1Aa*a*

For each land use, the ratios between the average K_s values of the topsoil, under slow and fast prewetting (Fig. 4a and b) were significantly and positively correlated ($y = 0.68x - 3$, $r^2 = 0.99$) with their slaking values (Table 2). However, this kind of correlation was insignificant for the topsoil of the three land uses. These results suggest that the differences in the K_s values between slow and fast prewetting in the topsoil of the various land uses (Fig. 4a and b) were mainly a result of the differences between their slaking values (Table 2).

For the soils from all three land uses, the range of swelling values under SW wetting was higher for the subsoil than for the topsoil: 75.4–88.5% and 51.6–71.5%, respectively (Table 2). This was, most likely, due to the higher ESP in the subsoil than in the topsoil layer (Fig. 3). These high swelling values in the subsoil layer decreased the volume of conductive pores in the soil (Ben-Hur et al., 2009), which, in turn, resulted in lower K_s values in the subsoil than in the topsoil layer (Fig. 4). In addition, the high swelling values in the subsoil probably masked the effects of the slaking forces on the K_s values, so that, in this soil layer, no significant differences were observed between the K_s values obtained under slow and fast prewetting, respectively (Fig. 4c and d).

The saturated hydraulic conductivity, EC and clay concentration in the leachate under deionized water leaching as functions of cumulative leachate volume are presented in Fig. 6 for the 0.9–1.2 m layer of the sesame soil with an ESP of 9.1%. In this case, the leaching with deionized water was after slow prewetting of the soil followed by leaching with three pore volumes of SW. The initial, i.e., zero leachate volume, K_s and EC values were those observed at the end of the leaching run with SW. The effects of soil leaching with deionized water on the K_s and EC values, after slow prewetting of the other soil samples from the various land uses and with diverse ESP values showed similar patterns to those observed with the sesame soil (Fig. 6), and therefore are not presented. The K_s and EC values decreased as the cumulative leachate volume increased, until steady-state values, i.e., those observed near the end of the leaching run, were obtained (Fig. 6). In this case the soil had been subjected to slow prewetting, therefore the slaking forces were negligible, and the K_s decline (Fig. 6a) must be attributed to two main processes (Chaudhari, 2001; Edelstein et al., 2010; Shainberg and Letey, 1984):

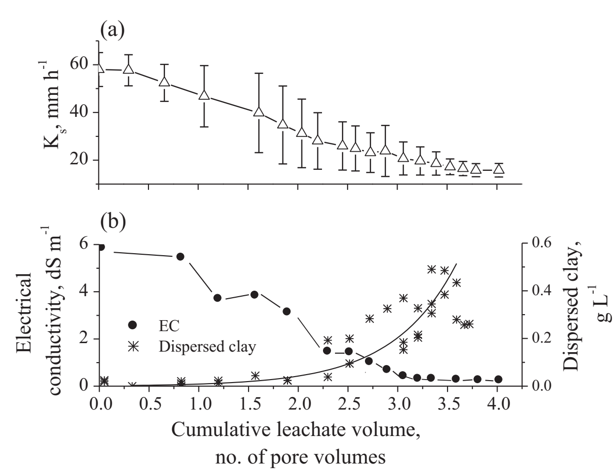

Fig. 6. (a) Saturated hydraulic conductivity (K_s) values, and (b) electrical conductivity and dispersed clay concentration in leachate under deionized water leaching, as functions of cumulative leachate volume for the 0.9–1.2 m layer in the sesame soil with an ESP of 9.1%. Bars indicate two standard deviations.

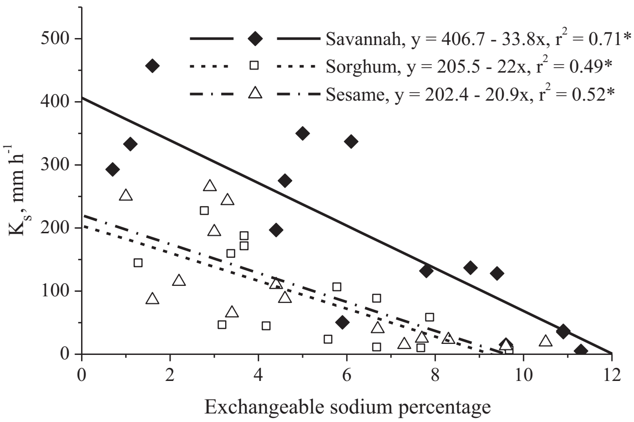

Fig. 7. Steady-state saturated hydraulic conductivity (K_s) of soils from different land uses under deionized water leaching, as functions of exchangeable sodium percentage, and their regression lines. *Indicates significant regression coefficients.

i. The decrease in the electrolyte concentration of the soil solution (Fig. 6b) led to increased soil swelling, which, in turn, diminished the conductive pore volume and the K_s. The swelling values of the subsoil layer from the three land uses increased from a range of 75.4–88.5% after wetting with SW to a range of 92.1–96.1% after wetting with distilled water (Table 2).
ii. Decreasing the electrolyte concentration of the soil solution below the flocculation value led to clay dispersion, as indicated by the occurrence of dispersed clay particles in the leachate (Fig. 6b). These dispersed particles blocked some of the conductive pores in the soil and further decreased its K_s.

The steady-state K_s values of the soil samples from the various land uses, after their slow prewetting and leaching with deionized water, along with their regression lines are presented in Fig. 7, as functions of ESP. For all three land uses, the steady-state K_s decreased linearly and significantly with increasing ESP. Because the ESP values were positively correlated with soil depth for each land use (Fig. 3), the steady-state K_s values were negatively correlated with soil depth as well. This decrease of the steady-state K_s with rising ESP (Fig. 7) was most likely because of increased soil swelling and clay dispersion (Keren and Ben-Hur, 2003; Shainberg and Letey, 1984). No significant differences were found between the K_s values of the soils cultivated with sorghum and sesame, respectively (Fig. 7), whereas, in contrast, the K_s values of the savannah soil were significantly higher than those of the cultivated soils ($P < 0.005$).

Dispersion and EC values of the suspension of the soils from the three land uses, as determined by the dispersion test, are presented

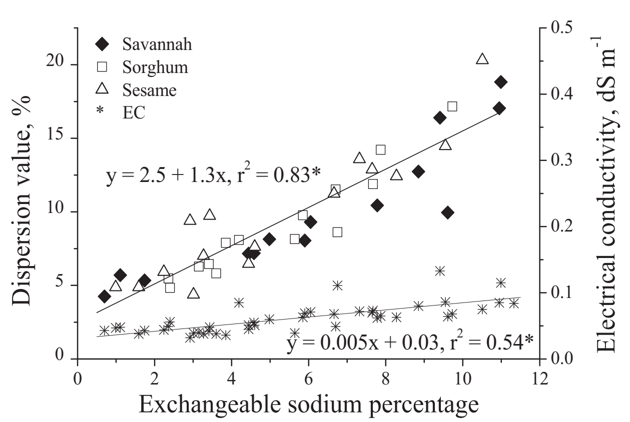

Fig. 8. Dispersion values and electrical conductivity of the supernatants as function of exchangeable sodium percentage for soil samples from different soil layers and various land uses. *Indicates significant regression coefficients.

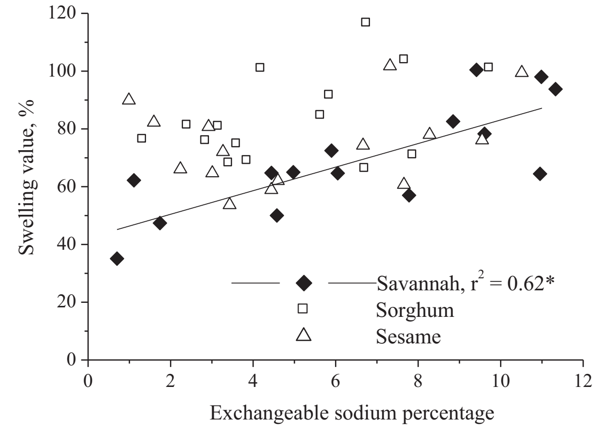

Fig. 9. Swelling values of soils from different soil layers in various land uses, as functions of exchangeable sodium percentage. *Indicates significant regression coefficient.

in Fig. 8 as functions of ESP. The EC values of the suspensions of all the soil samples were $<0.15\ dS\ m^{-1}$ (Fig. 8), i.e., below the flocculation values of the studied soils (Goldberg and Forster, 1990). The dispersion values were about 5% and about 18% in the low- and high-ESP soils, respectively (Fig. 8), which indicates that between 5 and 18% of the total clay content in the studied soils had the potential to disperse under soil leaching with deionized water. Within the ESP range studied, no significant differences were found between the dispersion values of the soils from the various land uses, therefore, a single significant linear regression was calculated for all the soil samples (Fig. 8). It can be concluded from these results that the higher steady-state K_s values of the savannah soil than of the cultivated soils (Fig. 7) were not due to differences in their sensitivity to clay dispersion.

Swelling values of the soil samples from each land use after wetting with deionized water, as determined by the swelling test, are presented in Fig. 9 as functions of ESP values. A significant positive linear regression was found for the soil samples from the savannah (Fig. 9), in which swelling values ranged from 36% with low ESP to 97% with high ESP, signifying increases of 136–197%, respectively, in the volumes of the aggregates. In contrast, no significant correlation between swelling and ESP values was found for the sorghum and sesame soils; however, their swelling values were, in general, higher than those of the savannah soil for ESP values <9 (Fig. 9). The differences in swelling values between the savannah and the cultivated soils were clearly manifested at the field scale, with cultivated soils exhibiting more extensive – deeper and wider – cracks than the savannah soil (Fig. 10). The higher swelling propensity of the sorghum and sesame soils than of the savannah soil (Figs. 9 and 10) may account for the significantly lower steady-state K_s values of the former (Fig. 7).

The dissimilarity among the soils from the various land uses, in their swelling and K_s values (Figs. 7 and 9; Table 2) could have resulted from the differing effects of the various land uses on abiotic and biotic factors. Abiotic mechanisms include tillage operations, which cause deterioration of the soil structure by decreasing organic matter content, increasing soil bulk density, reducing porosity, and compacting the soil (Chan and Hulugalle, 1999; Grant, 2008; Radford et al., 2000). However, such mechanical effects of tillage on Vertisol structure would be limited to a maximum depth of 0.4 m (Radford et al., 2000). The tillage in the experimental fields in the Humera district was non-intensive and, most likely, affected only the <0.2 m topsoil layer (Mizan Amare, personal communication). Thus, tillage of the sorghum and sesame fields does not explain the differences between the various land uses, in the steady-state K_s values of the deep (0.3–1.2 m) soil layer (Fig. 7).

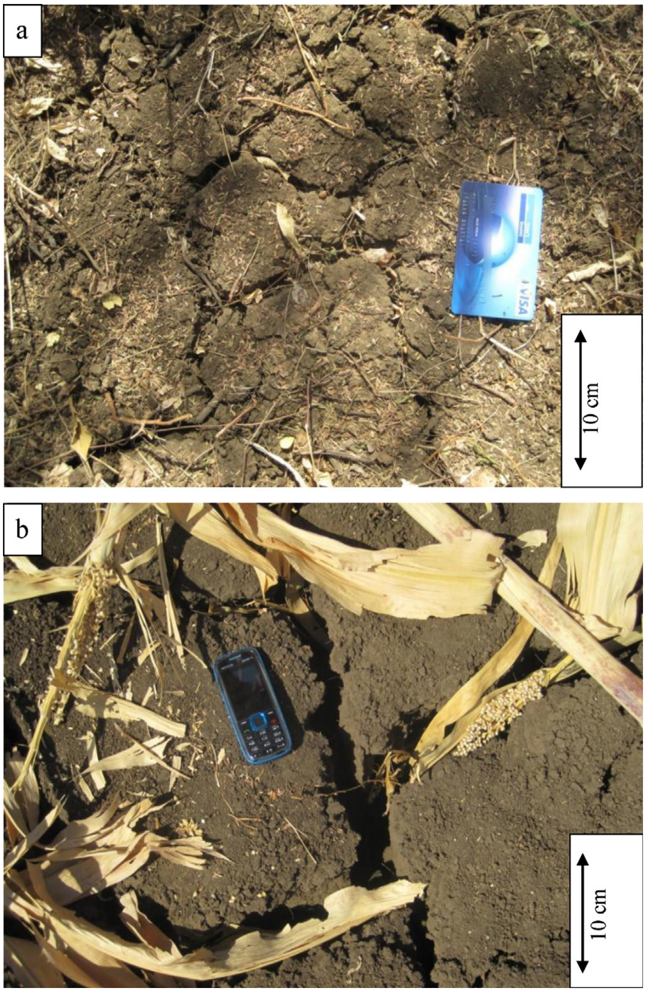

Fig. 10. Soil-surface cracking in the (a) savannah and (b) sorghum field. The pictures were taken in December 2010, 3 months into the dry season.

Sorghum and sesame are annual crops, grown in the rainy season and using most of the available soil water in a short time. After their harvest, the fields lie bare throughout the dry season, so that activity of plant roots and microflora/fauna, i.e., the biotic factors, in the soil are probably very low during this season. This suggests that the role of the biotic mechanism in improving soil structure in the sorghum and sesame fields was minor. In contrast, the *A. seyal* tree, which is the predominant plant in the savannah habitat, is a perennial tree that has lateral roots as long as 10 m, which can reach deeper than 1.2 m; these trees use the available water in the soil gradually throughout the year (Seghieri, 2008; Seiny-Boukar et al., 1992). *A. seyal* belongs to the family *Fabaceae* (*Leguminosae*), whose members develop symbiotic associations with mycorrhizae and nitrogen-fixing bacteria, and thereby promote biotic activities in the soil continuously throughout the year (Traoré et al., 2007). Such biotic activities would be expected to increase soil-structure stability (Bearden and Petersen, 2000; Blanchart et al., 2004; Chenu and Jaunet, 1990; Chenu, 1989). Furthermore, they may decrease soil swelling and enhance the K_s of the 0–1.2 m soil profile in the savannah habitat compared with those in the sorghum and sesame fields (Figs. 7, 9 and 10).

4. Summary and conclusions

1. Steady-state K_s values after slow prewetting and leaching with deionized water were significantly negatively correlated with soil ESP for the three land uses. The K_s values of the savannah soil were significantly higher than those of the cultivated soils down to a depth of 1.2 m. Differences between the land uses in their swelling values were, most probably, the main cause of the higher K_s values of the savannah soil than the cultivated soils.
2. It was suggested that abiotic and biotic mechanisms were responsible for the dissimilarities between the soils from the various land uses, in their swelling and K_s values. The cultivated soils, unlike the savannah soil, had been subjected to tillage, which adversely affected the topsoil structure. Because sorghum and sesame are annual crops, their biotic effects in improving soil structure were minor. In contrast, *A. seyal* trees, the predominant plants in the savannah habitat, are perennial, and therefore promote continuous biotic activities in the root zone throughout the year. It was hypothesized that these biotic activities increased soil structure stability, decreased soil swelling, and enhanced the K_s of the 0–1.2 m soil layer in the savannah.
3. For the three land uses, the subsoil (0.9–1.2 m) was more prone to swelling and dispersion than the topsoil (0.15–0.3 m), most likely, due to the higher ESP in the former than the latter. In contrast, the topsoil was more sensitive to slaking forces than the subsoil. The aggregates in the subsoil were subjected to high compaction because of overburden pressure, and this probably increased the cohesion forces between the particles in the aggregates, leading to higher resistance to slaking forces. In addition, the high swelling and dispersion in the subsoil layer probably masked the effects of the slaking forces in this soil layer.
4. The differing swelling values obtained for the three land uses were manifested at the field scale, at which the cracking was significantly more intense in the cultivated soils than in the savannah soil. These differences could have significant effects on water infiltration, runoff, and water distribution in the soil profiles in the various land uses under rainfall conditions. Additional study should be conducted to further understand these issues.

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