Estimation of Soil Hydrodynamic Parameters Related to Agricultural Practices—Case of the Tougou Experimental Site (Burkina Faso)

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Abstract: This study aims to estimate the hydrodynamic properties of soils under various agricultural practices in the Tougou catchment in northern Burkina Faso. The methodology adopted is based on the determination of the unsaturated hydraulic conductivity and capillary sorptivity close to saturation. This method relies on the measurement of the transient infiltration flux at the soil surface with imposed hydraulic head varying from -60 to -20 mm. These tests are carried out on control, stony line, half-moon and zai plots. The results show a difference in hydrodynamic parameters according to the agricultural practices. The unsaturated hydraulic conductivity is 33.1 cm/h, 13.1 cm/h, 20.3 cm/h and 4.0 cm/h for zai, control, stony line and half-moon plots respectively. The unsaturated hydraulic conductivity is 33.1 cm/h, 13.1 cm/h, 20.3 cm/h and 4.0 cm/h for zai, control, stony line and half-moon plots respectively. The pores participating to water transfer also differ. The mean size of drainable pores is 43.7, 56.2, 22.3 and 87.2 μm on control, stony line, half-moon and zai plots respectively.

Key words: Agricultural practice, unsaturated hydraulic conductivity, sorptivity, soil, Tougou, Burkina Faso.

1. Introduction

The Sahel of Burkina Faso, like all the Sahelian regions, undergoes for several decades various phenomena of natural and anthropogenic degradation of ecosystems. This degradation, accentuated by a decrease in rainfall over the last decades, causes a modification of the processes and mechanisms that govern these ecological units, which ultimately leads to a modification of the state and aspect of these ecosystems. The various anthropogenic actions combined with the rainfall deficit, cause a reduction of the vegetal cover, or even locally its disappearance. Indeed, in areas where vegetation has disappeared, it has developed on soil surface an indurated, continuous and impermeable layer (superficial crust). This layer set up is controlled by the action of the kinetic energy

of rainfall (splash effect) and runoff. It thus appears at landscape scale an imbalance in the spatial distribution of water, accentuating the constraining nature of this resource. To this, added anthropic pressures and the development of livestock farming thus increasing the vulnerability of the environment to drought [1].

The degradation of natural resources experienced by Sahelian countries in recent years limit their capacity for endogenous development. To increase their resilience to this, Sahelian farmers in Burkina Faso have adopted several agricultural practices for the water mobilization at the farm scale [2-7]. These practices, which appeared between 1980 and 1985 and are very demanding in terms of working time and physical effort, nevertheless constitute innovative alternatives for the development of a resilient agriculture in the Sahel. They consist of applying agricultural practices such as zai, half-moon and stony line and using of short cycle varieties. These

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techniques have allowed not only the restoration of many uncultivated lands [8], but also the improvement of cereal yields [9] and the increase of the groundwater level [10]. Fatondji, D., et al [8] reported that with the zai technique 100,000 to 300,000 ha of degraded land were rehabilitated in Burkina Faso while Roose, E., et al. [9] showed in the same country that under zai, sorghum yields are multiplied by about 1.6. These yield increases result from the combined effect of water retention, composting and supplemental manure fertilization.

In such context, knowledge of soil water transfer processes is a key priority. Thus, the present study is implemented on an experimental site in Tougou located in the north of Burkina Faso. It aims at estimating soil hydrodynamic properties related to several types of agricultural practices.

2. Material and Methods

2.1. Study Area

The study area is the Tougou catchment (between

Latitudes of 13°40' N, and longitudes of 2°13' W), a surface sub-catchment of Nakambe river in the north-east of Burkina Faso. It has a surface area of 37 km² (Fig. 1). The climate is semi-arid with a mean annual rainfall varying from 400 to 650 mm. Temperatures range between 18 and 40 °C. The dry season extends from October to May and the rainy season from June to September with peak precipitation generally recorded in July or August. Soils are cultivated or denuded (degraded) and the vegetation consists of savanna, shrub and grassy steppe.

The experimental design (Fig. 2) consists of two separate Fisher blocks A and B, the distribution of which is random. Each block consists of four plots of 200 m² (20 m long by 10 m wide) each receiving a specific treatment: direct seeding as a control plot (T0), a stony line plot (T1), a half-moon plot (T2) and a zai plot (T3). Zai (plot T3) is a complex system of restoring the productivity of degraded soils, a particular type of an open hole (20-40 cm in diameter and 10-15 cm deep), concentrating runoff and organic matter. The

Fig. 1 Location of Tougou surface catchment.

Fig. 2 Design of agricultural practices plots in Tougou experimental site.

spacing between the zai holes is $60 \text{ cm} \times 60 \text{ cm}$. The stony lines (plot T1) are constructed as a hydraulic barrier of polyform stones anchored 15 cm deep and located 15 m from plot upstream limit, parallel to the contour lines to dissipate surface runoff energy. Half-moons (plot T2) are semicircular holes of 4 m in diameter and 15 to 25 cm deep, and are excavated perpendicular to water flow direction. The spacing between half-moons is 2 m. The control plot (T0) is a direct seeding, in rows, as practiced in the locality. The spacing between seedlings on the control, stony-line and half-moons plots is $50 \text{ cm} \times 50 \text{ cm}$. An organic amendment (cow dung) of 5t/ha is applied to each plot prior to seeding and a microdose application of NPK (Nitrogen, Phosphorus, Potassium) fertilizer (2-4g per hole) after crop emergence and urea (1 g per hole) at the run [11, 12]. Plots are grown with a 70 days cycle millet variety (Kiipalla). The choice of this variety is justified by its precocity, its resistance to drought and its wide adoption by local farmers.

2.2 Field Data Collection

Measurements of the unsaturated hydraulic conductivity are implemented using disc infiltrometer on all eight plots of the experimental site. On each plot, the infiltrometry tests are carried out at suctions 20, 40 and 60 mm with a repetition of 3 measurements per suction and the average value was recorded. Before

starting and ending each test, soil samples are analyzed in order to estimate the initial and final water contents.

2.3 Data Processing

2.3.1 Unsaturated Hydraulic Conductivity and Capillary Sorptivity

The three-dimensional cumulative infiltration per unit of area, I (mm) for the entire time range, can be expressed by Eq. (1) [13].

$$\begin{aligned} & \frac{2(K_0 - K_n)^2}{S_0^2} t \\ &= \frac{2}{1 - \beta} \frac{K_0 - K_n}{S_0^2} \left\{ I_{3D} - K_n t \left[\frac{\gamma S_0^2}{R_D(\theta_0 - \theta_n)} \right] t \right\} \\ & - \frac{1}{1 - \beta} \ln \left\{ \exp \left[\frac{2\beta(K_0 - K_n)}{S_0^2} \right] \left[I_{3D} - K_n t \right. \right. \\ & \left. \left. - \left(\frac{\gamma S_0^2}{R_D(\theta_0 - \theta_n)} \right) t \right] + \beta - 1 \right\} \beta^{-1} \end{aligned} \quad (1)$$

where R_D (m) is the radius of the disc; θ_0 and θ_n are the final and initial volumetric water content ($\text{m}^3 \cdot \text{m}^{-3}$), respectively; S_0 is the sorptivity ($\text{m} \cdot \text{s}^{-0.5}$) for θ_0 ; and γ is the proportionality constant, the value of which can be approximated to 0.75 [14]; K_0 and K_n are the soil hydraulic conductivity values ($\text{m} \cdot \text{s}^{-1}$) corresponding to θ_0 and θ_n , respectively; and β is a shape constant that commonly takes an average value of 0.6 [14]. In spite of its relative complexity, Eq. (1) is valid for the entire

time range, from $t = 0$ to $t = \infty$. However, taking into account that infiltrometer experiments do not require very long time ranges of application, Haverkamp, R., et al. [13] established that, for short to medium time and assuming $K_n \approx 0$, Eq. (1) can be simplified to

$$I_{3D} = C_1 \sqrt{t} + C_2 t \quad (2)$$

Where

$$C_1 = S_0 \quad (3)$$

$$C_2 = \frac{2 - \beta}{3} K + \frac{\gamma S_0^2}{R_D(\theta_n - \theta_0)} \quad (4)$$

Using this expression, Vandervaere, J., et al. [15] proposed the differentiated linearization method to infer soil hydraulic properties using linear regressions. The technique consists in differentiating Eq. (2) with respect to the square root of time.

$$\frac{dI}{d\sqrt{t}} = C_1 + 2C_2\sqrt{t} \quad (5)$$

And next plotting the $\frac{dI}{d\sqrt{t}}$ term as a function of $\sqrt{t}$.

The C_1 is the intercept and C_2 is the slope of the corresponding regression lines. According to the authors, the differentiated linearization technique allowed visual monitoring of the contact layer, when used, eliminating its influence on the estimates of the soil hydraulic properties.

2.3.2 Mean Size of Drainable Pores

The knowledge of the capillary sorptivity S_0 and of the hydraulic conductivity K has been used by some authors [16, 17] to define the capillary length λ_c which is a macroscopic scale expressing the relative importance of the capillary and gravitational forces acting on water penetration in the soil. Its mathematical formulation is as Eq. (6):

$$\lambda_c = \frac{b S_0^2}{(\theta_n - \theta_0) K} \quad (6)$$

Where b is 0.55, a value generally accepted for most soils [18]. Using the elementary laws of capillarity, Philip, J. R. [16] introduced the mean size drainable

pores, λ_m , given by Eq. (7):

$$\lambda_m = \frac{\sigma}{\rho_w g \lambda_c} \quad (7)$$

Where σ is the surface tension coefficient of water (0.072 N/m at 25 °C), ρ_w the density of water (1,000 Kg/m³) and g the acceleration of gravity (9.81 m/s²). By introducing in Eq. (6), the numerical values of σ , ρ_w and g are obtained by expressing λ_m in μm Eq. (8):

$$\lambda_m = 13.3 \frac{(\theta_n - \theta_0) K}{S_0^2} \quad (7)$$

3. Results and Discussion

3.1 Results

3.1.1. Unsaturated Hydraulic Conductivity and Capillary Sorptivity

The unsaturated hydraulic conductivity and the capillary sorptivity according the suction follow a logarithmic law and change in a decreasing manner when the suction increases on all the plots. As an illustration, the evolution on the plot T3A of these two parameters as a function of the suction is represented in Fig. 3.

On each of the two blocks of the experimental site, the highest unsaturated hydraulic conductivity values (Table 1) are found in the zai plots and the low values in the control plots. With regard to the sorptivity values, the half-moon plots show the highest values whereas the zai plots show the lowest values.

3.1.2. Mean Size of Drainable Pores

The distribution of mean size of pore as a function of agricultural practices (Fig. 4) indicates that the maximum of pores participating to the flow is recorded on zai plots. This is totally in agreement with the results obtained for the unsaturated hydraulic conductivity. This is certainly due to the amendment in organic matter made on this practice which allows increasing the microbiological activity of the soil. The latter tends to favor the creation of a preferential flow path for water in the soil, hence the importance of the infiltration capacity of this practice.

Fig. 3 Distribution according to the suction of unsaturated hydraulic conductivity and capillary sorptivity on plot T3.

Table 1 Unsaturated hydraulic conductivity (K) and capillary sorptivity capillaire (S₀) recorded at a suction 40 mm.

Plot	K (mm/s)	S ₀ (mm/s ^{1/2})
T0A	0.031 ± 0.008 ^a	0.052 ± 0.003 ^b
T1A	0.048 ± 0.005	0.042 ± 0.008
T2A	0.009 ± 0.001	0.067 ± 0.010
T3A	0.086 ± 0.012	0.029 ± 0.002
T0B	0.042 ± 0.008	0.040 ± 0.005
T1B	0.065 ± 0.010	0.034 ± 0.006
T2B	0.013 ± 0.0002	0.044 ± 0.004
T3B	0.098 ± 0.012	0.021 ± 0.005

a: Variation coefficient for hydraulic conductivity; b: Variation coefficient for capillary sorptivity.

3.2 Discussion

The infiltrometry tests demonstrate that unsaturated hydraulic conductivity and sorptivity decrease with increasing suction. Indeed, these two parameters which follow a logarithmic law, vary with soil water content and the suction. At suctions close to saturation, the movement of water is controlled by the coarsest macroporosity. The soil has a high hydraulic conductivity associated with high porosity. As the soil becomes unsaturated, the larger pores are emptied and the flow occurs in smaller and smaller pores with more and more tortuous flow paths. These results confirm a

pronounced differentiation of these soils according to the agricultural practice with the consequence of an accentuation of the spatial discontinuity, as well from surface roughness as of their hydraulic behavior. In addition to highlighting this diversity of surface conditions, the analysis of the results obtained with regard to the hydraulic properties of the surface reveals a strong variation of the infiltration capacity. The highest values are found on the zai plots while the lowest values are found on the control plots. These differences are undoubtedly attributable to the reorganization of land cover by the implementation of the agricultural practices because a modification of the

Fig. 4 Distribution according to agricultural practices of mean size of drainable pores.

organization of the poral system of the superficial horizons leads to a reduction of the hydraulic conductivity close to saturation [15, 19, 20]. The hydraulic conductivity values estimated on the control plots correspond to those found on degraded soils. It reflects the hydrodynamic behavior of soils consisting generally of glaciais having a superficial layer characterized by a low infiltration capacity due to a reduced porosity, which appears this laminate coating to a real hydraulic barrier which strongly limits the water inflow in the soil. This type of land cover generates large runoff and correlatively leads to a very low accumulation of water in the soil. The hydraulic conductivity values estimated on the zai and stony line are larger than those of the control plot. Both of these agricultural practices tend to improve the infiltration capacity of the soil. For zai, the destruction of the upper soil layer will favor the capture of runoff, its solid and soluble load, and tends to increase the infiltration capacity [21]. This leads to high hydraulic conductivity values resulting from the improvement of the soil roughness. Indeed, runoff management, manure conservation and the concentration of nutrients will create conditions for optimum water transfer in the soil

through the generation of preferential flow paths (high termite activity). Concerning the stony line plots, improvements in hydrodynamic parameters are not very significant compared to the control plot in that the experimental design is in its second year of existence and several studies [22, 23] carried out in this region of Burkina Faso showed that such practice becomes efficient after three years. The results obtained on the half-moon show very low values compared to those of the control plot. This is certainly due to the fact that this agricultural practice tends to carry a lot of suspended matter which during the settling phase will clog the soil thus making the infiltration capacity very weak. The comparison of infiltrometry tests show that unsaturated hydraulic conductivity and sorptivity do not always change in the same way. In fact, the decrease of the hydraulic conductivity is much faster than that of the sorptivity. This behavior is due to several factors among which one can mention the presence of a vesicular porosity which reduces the capacity of infiltration. This vesicular porosity appears following the rains and is formed by trapping air during heavy rainfall. Indeed, some authors [24] have shown that in arid zone, the hydrodynamic characteristics of

superficial microhorizons could be affected by the appearance of these vesicles. This vesicular porosity is linked to the existence of an underlying microhorizon with low porosity, most often a material with low gas diffusivity [24]. This results in a reduced hydraulic conductivity of the superficial organizations. However, several authors have shown that in the Sahelian zone, it is the hydrodynamic characteristics of superficial microhorizons which condition, to a large extent, the infiltrability of the whole soil. It is therefore possible to consider the presence of these vesicles close to the surface as an index of low permeability [24] because the statistical analysis shows a very good relationship between the abundance of these pores and the runoff ability [25].

Numerous field or laboratory studies on undisturbed soils have shown a very significant increase in hydraulic conductivity close to saturation. This increase is generally greater than that expected from an exponential relationship of $K(h)$, a relationship often verified in soil physics for remolded soils or with a particularly homogeneous structure [26]. Jarvis, N. J. and Messing, I. [27] have shown that, for several soils, this increase was particularly marked for water heads greater than -60 mm, i.e. when pores of equivalent radius greater than 0.25 mm participate to the flow. These authors attribute these observations to the effect of soil macroporosity, defined as the set of pores with an equivalent radius greater than 0.25 mm (thus visible to the naked eye) participating to water transfer.

4. Conclusion

This study revealed that unsaturated hydraulic conductivity and sorptivity decrease with increasing suction. The hydrodynamic behavior of the soils under agricultural practices reveals a strong variation of the infiltration capacity. The highest values are found on the zai plots while the lowest values are found on the control plots. The unsaturated hydraulic conductivity is 33.1 cm/h, 13.1 cm/h, 20.3 cm/h and 4.0 cm/h for zai, control, stony line and half-moon plots respectively.

The pores participating to water transfer also differ. The mean size of drainable pores is 43.7, 56.2, 22.3 and 87.2 μm on control, stony line, half-moon and zai plots respectively.

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