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LAND DEGRADATION IMPACT ON WATER TRANSFER OF SOIL-PLANT-ATMOSPHERE CONTINUUM IN THE BURKINABE SAHEL

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ABSTRACT

This research conducted in the Tougou watershed located in North of Burkina Faso aims at assessing the impact of soil degradation on the water transfer in the soil-plant-atmosphere continuum. Field measurements were performed through an experimental design made of plots measuring 1 m^2 each and established on three sites of the watershed: three plots on an erosion crust (PZN), three plots on a desiccation crust supported herbaceous (PZD) and three plots on an area cultivated in sorghum (PZC). Each site was equipped with tensiometric and neutron tubes to measure pressure head and water content of the soil. Results showed that PZN was characterized by a low infiltration capacity enhancing runoff. The water stored during the rain periods is low and remains localized within the first 30 or even 40 cm top of soil, which promoted a quick evaporative recovery in days following the rainy event. PZD and PZC were characterized by a good hydraulic conductivity and a high infiltration speed. The infiltrated water was important and the drainage beyond the depth of 70 cm was observed during important rain events. The real daily average evapotranspiration varied between 3 and 4 mm on the all sites.

Keywords: Soil crust, sandy deposits, water balance, soil hydrodynamic properties, Sahel

RESUME

Cette recherche menée dans le bassin versant de Tougou situé au Nord du Burkina Faso vise à évaluer l'impact de la dégradation des sols sur le transfert de l'eau dans le continuum sol-plante-atmosphère. Les mesures de terrain ont été réalisées grâce à un modèle expérimental en parcelles de 1 m^2 chacune et effectuées sur trois sites du bassin versant: trois parcelles sur une croûte d'érosion (PZN), trois parcelles sur une croûte de dessiccation supportant les herbacés (PZD) et trois parcelles sur un espace cultivé en sorgho (PZC). Chaque site a été équipé de cannes tensiométriques et de tubes neutroniques pour mesurer respectivement la charge de pression et la teneur en eau du sol. Les résultats ont montré que PZN a été caractérisé par une faible capacité d'infiltration favorisant ainsi le ruissellement. L'eau stockée pendant les périodes de pluie est faible et reste localisée dans les premiers 30 ou même 40 cm supérieurs du sol ; ce qui a favorisé une reprise évaporatoire rapide durant les jours suivant l'événement pluvieux. PZD et PZC ont été caractérisés par une bonne conductivité hydraulique et une grande vitesse d'infiltration. L'eau infiltrée était importante et le drainage au-delà de la profondeur de 70 cm a été observé au cours des événements de pluie importantes. L'évapotranspiration réelle moyenne journalière a varié entre 3 et 4 mm sur tous les sites.

Mot clés : Croûte de sol, dépôt sableux, bilan d'eau, propriétés hydrodynamiques des sols, Sahel

INTRODUCTION

Physical degradation is one of the major features of the Sahelian soils. It is favored by the climate and a permanent land use (Visser, 2004). These changes have had significant repercussions on the region and have been proved to be highly incompatible with a sustainable development. They cause serious problems of availability and access to natural resources to populations. Indeed,

difficulties encountered while trying to make productive these drylands are not negligible, and have for a long time discouraged farmers who preferred to clear easy lands to cultivate from uplands and plateaus. Demographic pressure increasing more and more, fallow periods of these uplands have been shortened and problems of fertility renewal have been posed (Thiombiano, 2000). Meanwhile, severe climatic events have highlighted the importance in a certain number of situations of irrigation water supply supported by the presence of a water table, as in the case of shallows.

Different climatic crises in the Sahel have actually not changed rainfall severity and characteristics of extreme events such as the maximum height of the daily rainfall decadal frequency (Albergel, 1987). Despite the decline in rainfall, rain still intense, crumbling soil surface and make them susceptible to wind erosion (Valentin, 1991). This wind erosion is increased by higher frequencies of dry tornadoes before the rainy season (Serpentié et al., 1992).

Thus, we assist a degradation of Sahelian natural environment due to climate aridity which is increased and aggravated by a soil desiccation (Casenave and Valentin, 1989) mainly due to the degradation of surface: the reduction of vegetation cover exposes the soil without protection during the rainy season, often violent, and promotes intense diffuse runoff. This gives rise to dandruff area organizations that limit the infiltration capacity of the soil and prevent the penetration and accumulation of deep water reserves used by the vegetation which, consequently, shrinks more and more, revealing the nude areas eroded soils increasingly stretches where degradation processes are at their maximum extent.

Furthermore, superposed anthropogenic pressures and overload livestock leading to further weaken the area that is plagued by serious problems of desertification (Thiombiano, 2000). In fact, when the vegetation cover-soil system is disturbed, the soil is subject to high-intensity rainfall and streaming related to the fact that the concentration of water increases and the hydraulic properties of these soils (capping and infiltration dynamic, soil moisture) vary in time when the natural balance is disturbed (Casenave and Valentin, 1989).

One of the main changes concerns the water cycle. Indeed, the various human activities combined with the lack of rainfall have caused a reduction of the spatial extent of vegetation cover, or even, locally, its disappearance (Marchal, 1983). In areas where vegetation has disappeared, it has been developed on the soil surface, under the action of the kinetic energy of rain (splash effect), a continuous hardened film, with a very low permeability (erosion crust), which constitute a much more favorable environment for streaming than infiltration

(Casenave and Valentin, 1989). The versants have become transit zones for surface water flow and low areas as surface accumulation.

It thus appears an imbalance in the spatial distribution of water across the landscape that enhances the binding effect of this parameter. On that, it is also added the anthropogenic pressures and overload of livestock (Thiombiano, 2000) leading thus to further weaken the environment which is plagued by serious problems of desertification (Karambiri, 2003). This desertification has an important impact on soil productivity. This basin, originally cultivated, has seen over years and climatic hazards, migration of the population and an increase of degraded areas.

MATERIALS AND METHODS

Study area

The study has been conducted during 2006 in the experimental drainage basin of Tougou (13°40'56''N, 2°13'39''E), of about 37 km² size, located in the Sahelian zone of Burkina Faso. The basin has experienced many sequences of dry and humid cycles during the last half-century (Badou, 2006). The climate of the basin is Sudano-Sahelian, The average annual cumulated rainfall for the 1961 - 2011 periods shows a high temporal variability (636±148 mm). Soils of the basin are generally kind of little change; they are locally associated with indurate tropical ferruginous soils.

Experimental design

Experimental sites were set up on each one three different types of soil surface (Casenave and Valentin, 1992) frequently observed in the study area:

- PZN site is located in an area with an erosion crust. The soil surface is compact. It is characterized by a glazing phenomenon and, a clogged less-functional porosity. This soil surface state is devoid of any vegetation;
- PZD site is located in an area with a drying crust. The soil surface is characterized by a sandy micro-horizon (40-50 cm) slightly compacted.

This soil surface type presents an important functional porosity. It supports the essential of the natural vegetation of the watershed;

- PZC site is located on a cultivated area. It consists of waterlogged soils, associated with ferruginous tropical soils prevailing in the floodplains. These soils are favorable for growing cereals and irrigated vegetables during the rainy and dry season respectively.

The plots of 1 m^2 set up in three repetitions on each one of these three sites were equipped with a device to measure the different components of the water balance. Besides, the watershed is equipped with ten pluviometers, four recording rain gauges and one weather station recording temperature, sunshine, wind's direction and speed.

Implementation of the experiment and determination of the soil hydraulic parameters and the water balance components

On each site, bulk density and porosity were determined on undisturbed samples; soil particle size and soil organic matter were determined on disturbed samples, taken at each 10 cm up to 70 cm depth.

The water content of the soil was daily recorded at a fixed time (07 am), with a neutron probe through access tubes set up vertically up to 80 cm depth in each site (one tube per site). The measurements have been made every 10 cm up to 70 cm depth. First measure was exceptionally taken in a layer of 15 cm thickness. Values of the pressure head of the soil water were recorded by tensiometers set in each site, at five different depths (10, 20, 30, 40 and 80 cm).

The runoff has been estimated on a plot of 1 m^2 enclosed by a metal frame, the runoff flow is transferred to a reception barrel, located downstream the plot. Drainage has been estimated at the reference depth of 70 cm from the tensiometric measurements taken at 60 and 80 cm after determining hydraulic conductivity function $K(h)$ using a disc infiltrometer with controlled suction. The relationship (1) was used to determine the drainage.

$$D = \overline{q}\Delta t \quad (1)$$

where $\overline{q}$ is the average water flux over the time interval Δt corresponding to two successive measurements of the pressure head. Darcy's equation (2) was used to determine water flux.

$$q = -K(h)\frac{dH}{dz} \quad (2)$$

where q [LT^{-1}] is the water flux, K(h) [LT^{-1}] is the unsaturated hydraulic conductivity and $\frac{dH}{dz}$ is the hydraulic gradient head in which H [L] is the hydraulic head and z [L] is the depth at which the pressure head h [L] was measured. H and z are connected by the equation (3):

$$H = h - z \tag{3}$$

The soil water storage WS [L] from the soil surface to 70 cm was determined using equation (4) proposed by Doto et al. (2015):

$$WS = (\theta_{10} \times 150) + (\theta_{20} \times 100) + (\theta_{30} \times 100) + \ldots\ldots + (\theta_{70} \times 50) \tag{4}$$

where θ_i [L^3L^{-3}] is the water content at the depth $i = 10, 20 \ldots., 70$.

These various parameters were used to determine the last term of water balance represented by the actual evapotranspiration. The relationship used for this purpose was:

$$ET_a = P - \Delta WS - R - D \tag{5}$$

where ET_a [L] is the actual evapotranspiration of the existing vegetation, P [L] is the rainfall, R [L] is the surface runoff, D [L] is the soil water drainage, ΔWS [L] is the change of the soil water storage in the soil layer 0-70 cm during the growing period of 2006.

The evolution of the soil surface properties was monitored by means of tests carried out with:

- A double-ring infiltrometer with respective internal and external diameters of 25 and 33 cm. This test performed under a constant water head of 3 cm has provided the steady infiltration rate K_s. As for infiltration and hydraulic conductivity capacities when the soil surface is saturated, they have been determined using the method of the double ring (Infiltrometer of Müntz). During the test, a constant water head of 3 cm was maintained at the ground surface until to reach the steady state. Twelve repetitions have been made at each measurement site;
- A tension disk infiltrometer with 100 mm of diameter implemented under a pressure head at the disk of -40 mm. The hydraulic conductivity under negative charge has been determined using a disc infiltrometer with controlled suction. At each site, measures have been done with eight repetitions under above pressure head of - 40 mm.

In both cases, the measurements were repeated three times. The tests performed by means of the disk infiltrometer were analyzed according to the procedure described by Vandervaere et al. (2000a) who proposed an expression similar to the equation of Philip (Philip, 1969) for characterizing the transitory unidimensional axisymmetric infiltration starting from a circular source on the ground surface, namely:

$$I = C_1\sqrt{t} + C_2 t \tag{6}$$

where I [L] is the cumulated infiltration depth and t [T] is the time. C_1 and C_2 are coefficients which can be estimated with the equations established by Haverkamp et al. (1994):

$$C_1 = S \tag{7}$$

$$C_2 = \frac{2-\beta}{3}K + \frac{\gamma S^2}{r(\theta_0 - \theta_i)} \tag{8}$$

where S $[L.T^{-1/2}]$ is the capillary sorptivity, K $[L.T^{-1}]$ is the hydraulic conductivity, γ is a constant equal to 0.75, β is a parameter ranging between 0 and 1, depending on the type of soil and the applied pressure head, r [L] is the radius of the disk, θ_i and θ_o $[L^3L^{-3}]$ are the initial and final water content respectively. The advantage of the method is that it does not require any estimation of the permanent flow and thus takes less time. On the other hand, it provides only an interval of values for hydraulic conductivity K, between K_{min} for $\beta = 0$ and K_{max} for $\beta = 1$. Vandervaere (1995) proposes to use a value of β equal to 0.6 (assuming a lognormal distribution law for the hydraulic conductivity) for the calculation of the hydraulic conductivity.

Our tests were analysed by the "differentiated linearization method" (Vandervaere et al., 1997; Vandervaere et al., 2000b). This method consists of differentiating the cumulative infiltration data with respect to the square root of time. Applying this differentiation on equation (6) gives:

$$\frac{dI}{d\sqrt{t}} = C_1 + 2C_2\sqrt{t} \tag{9}$$

Thus, plotting $dI.t^{-1/2}$ vs. $t^{1/2}$ should be linear, with C_1 equal to the intercept and C_2 the half-slope of the regression line. The values of the sorptivity S and of the hydraulic conductivity K can be deduced from equation (7) and equation (8). These values have been used by certain authors (Philip, 1985; White and Sully, 1987) to define the capillary length λ_c [L] which expresses the relative importance of the capillary and gravitational forces acting on the penetration of water into the soil. Its mathematical formulation is:

$$\lambda_c = \frac{bS^2}{(\theta_o - \theta_i)K} \quad (10)$$

where b is a parameter depending on the form of the relationships between the hydraulic conductivity and the pressure head, on the one hand, and between the water content and the pressure head, on the other hand; a value of 0.55 has frequently been considered as an appropriate approximation for the majority of soils (Warrick and Broadbridge, 1992). By using the elementary laws of capillarity, Philip (1985) introduced the average dimension of the hydraulically functional pores λ_m, given by the following equation:

$$\lambda_m = \frac{\sigma}{\rho_w g \lambda_c} \quad (11)$$

where σ $[MLT^{-1}]$ is the water surface tension, ρ_w (ML^{-3}) the water density and g $[L^2T^{-1}]$ the acceleration due to gravity. By introducing into equation 6, the values of σ (0.072 $N.m^{-1}$ at 25°C), ρ_w (1000 $kg.m^{-3}$) and g (9.81 $m^2.s^{-1}$), one obtains, expressing λ_m in µm:

$$\lambda_m = 13.3 \frac{(\theta_o - \theta_i)K}{S^2} \quad (12)$$

RESULTS

Evolution of hydraulic properties

Sixteen tests have been performed during the rainy season of 2006 (24 with a double ring and 36 with a disc infiltrometer). The results obtained are reported in Table 1.

Table 1 : Mean values and standard deviation of the saturated hydraulic conductivity (K_s) and the unsaturated hydraulic conductivity (K) measured under a pressure head of -40 mm in the three experimental sites.

Sites	PZN	PZD	PZC
K_s ($mm.h^{-1}$)	3.0±0.34[d]	9.5±0.22	14.8±0.37
K ($mm.h^{-1}$)	2.3±0.15	4.8±0.30	7.3±0.31
Texture	Silty clay	Sandy clay loam	Sandy loam
Organic contents (%)	2.0	1.2	0.7

[d]*Represent standard deviation*

A further consideration of Table 1 showed significant differences between the different measurement sites for both parameters. The highest values occur on cultivated zone site and lowest values are from the site on erosion crust. These differences between the three sites was probably attributable to the reorganization of the surface state as any change occurs the organization of the porous system of superficial horizons may affect both the saturated and unsaturated hydraulic conductivities. The cultivated zone and the drying crust places were mainly made of sandy deposits from wind and water erosion that may promote infiltration than streaming which explain the higher values of the saturated hydraulic conductivity obtained in these two sites. As for the site of erosion crust, low values can be explained by the presence of a completely compacted surface layer that favors streaming (Ribolzi et al., 2000) through a reduction of macroporosity. Data in Table 2 showed that the average functional pore size varied in the same way than hydrodynamic parameters.

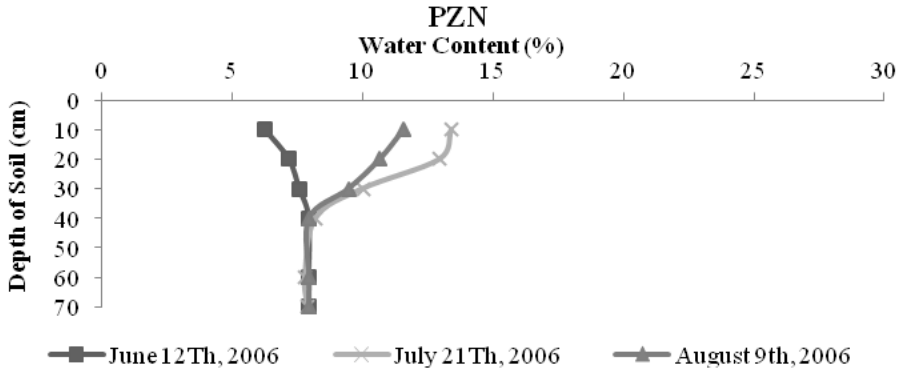
Table 2 : Average dimension of the functional pores on the three experimental sites

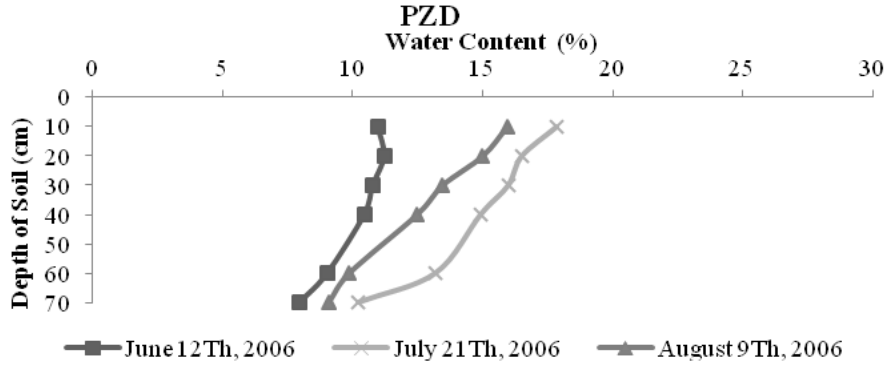
Sites	PZN	PZD	PZC
λ_m (mm)	0.094±0.23	0.185±0.32	0.219±0.19

Temporal evolution of the soil water content

Changes in the soil water content on the PZN site occurred mainly within the upper horizons (the thirty first centimeters). Below 40 cm, the soil water content remains practically constant at a very low level, inferior to 8% (Figure 1). This suggests that precipitations do not almost have effects beyond 70 cm depth and the drainage below 50 cm depth was negligible. This site was characterized by a low availability of water which was not enough to supply crops water requirement, except for few annual dwarfs. The main cause of this fact lies in the superficial encrusting resulting mainly from the deterioration of the surface structure of the soil.

As for the PZC and PZD sites, variations in water content was more important than within the PZN site, including at 70 cm depth, suggesting a probable drainage process at this depth.





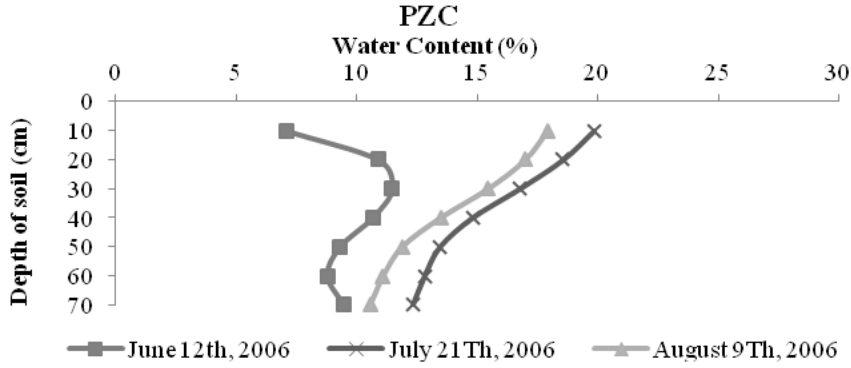


Figure 1 : Temporal evolution of the water profile on each site in 2006

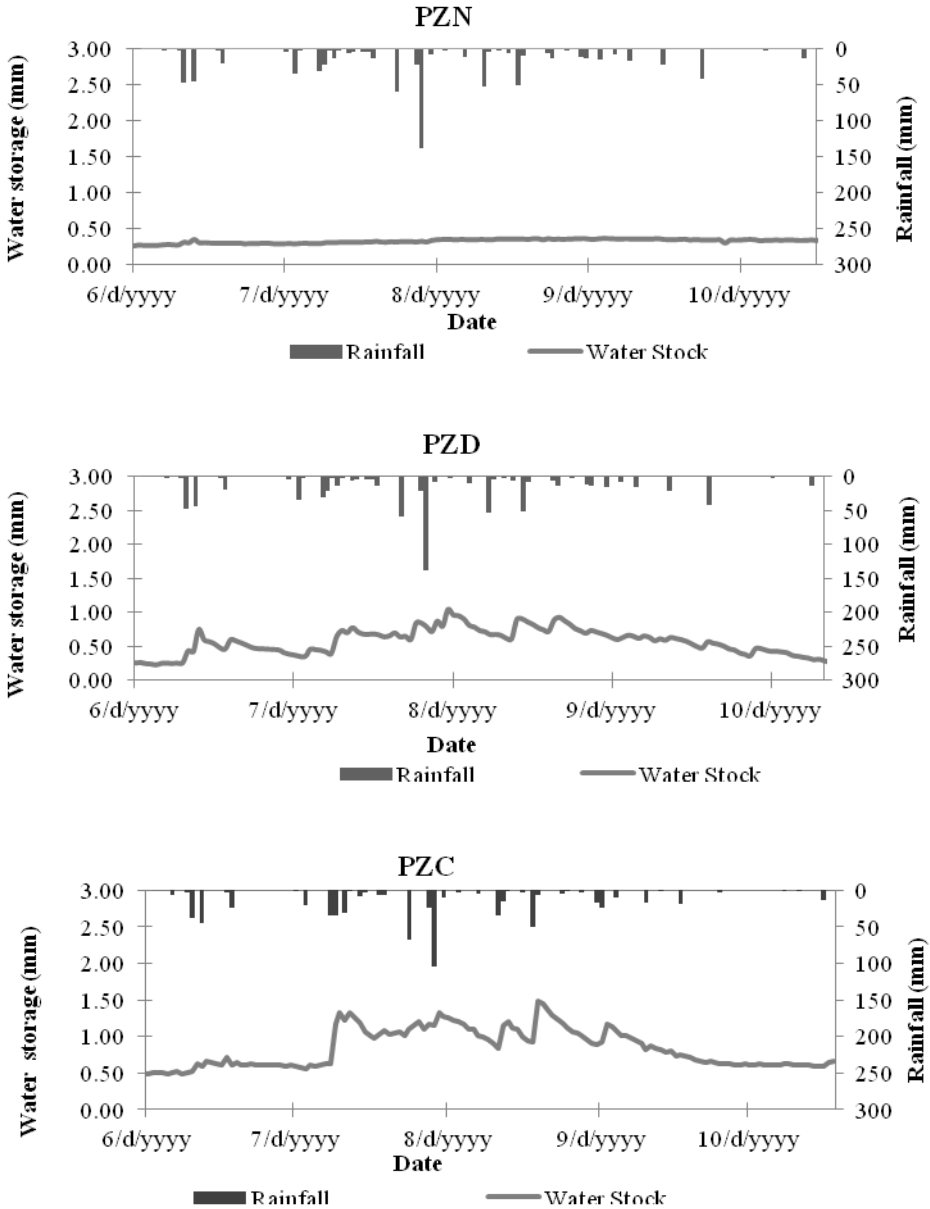


Figure 2 : Temporal fluctuation of the water stored at 70 cm depth on the various sites in 2006

Assessment of the water storage between the surface and 70 cm depth

Figure 2 shows the temporal evolution of the water storage within the soil surface and 70 cm depth. For all three sites, it was observed that the water storage remains relatively poor compared to the important cumulated rainfall. Infiltrated water was only stored superficially (within the first 40 centimeters) for the PZN site, which favored a rapid evaporative recovery during days following the rainy events. However, for other sites, enough water was accumulated within the soil.

Further consideration of Figure 2 reveals that in 2006, the water storage varied between 10 and 40 mm on the PZN site, whereas it can reach 100 mm on PZD and 150 mm on PZC. This greater amount of accumulated water can be explained by a higher infiltration capacity due to surface conditions which are more favorable for infiltration of runoff (streaming).

During periods without rain (June 29th to July 14th and from 6th October to 27th October, 2006), all the three sites experienced a significant decrease in water content.

Water balance components

The study of the water balance was carried out from June 12th to October 28th, 2006, period during which tensiometric measurements were available. The values of the various components of the water balance, illustrated in Figure 3, showed that actual evapotranspiration reached 27% of the rain on the site PZN whereas it is between 49 and 50% on the other sites (PZC, and PZD). This difference is related to decrease lower initial water content and to the absence of vegetation on the site PZN exposed only to evaporation, whereas on the other sites, the extraction of the water from the soil is due to the combined effects of evaporation and transpiration (Descroix et al., 2012).

On a daily basis, the average values of the actual evapotranspiration varied between 3 and 4 mm/day and are weak compared to the potential values (about 6 mm/day). The difference could be explained by the low rainfall observed in 2006 which resulted in a reduced availability of soil water to satisfy the evaporative demand. The entire previous elements made it possible to highlight two main different surface types:

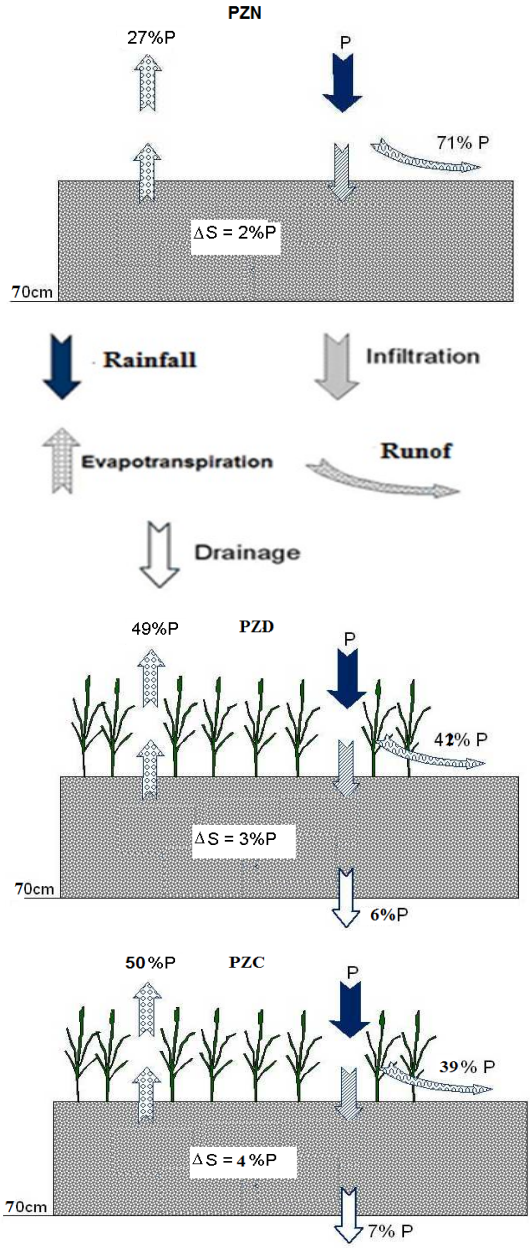


Figure 3 : Water balance components on the different sites for the period of June 12th to October 28th, 2006

i) Runoff type surface corresponding to site PZN: On this site, the existence of a thin superficial film (plasmic layer) made of fine compacted particles results in a reduction of the infiltration capacity due to a reduced porosity, assimilating these pellicular organizations to a hydraulic barrier which strongly limits water infiltration into the soil (Casenave and Valentin, 1989). Such surfaces are generally bare and generate important runoff resulting in a very weak accumulation of water in the soil. Infiltration affects only the surface horizon where most of the moisture fluctuations occur (Valentin et al., 2004). Similar results have been obtained by Hiernaux et al. (2009) that showed a 5% yearly decrease in yields related to soil degradation. Within the framework of a simulation of impacts of climate change effects and land use, Séguis et al. (2004) obtained runoff ratios that can vary by up to a factor of three between degraded and non-graded soils.

ii) More permeable surfaces corresponding to sites PZC and PZD: The absence of a surface film creates conditions more favorable to infiltration, which results in a more important accumulation of water in the soil. In some cases (site PZC), water transfer in the subsurface horizons is facilitated by the presence of roots.

DISCUSSION

The differentiated behavior of soil surface types showed the complex nature of the constitution and functioning of the Sahelian soils. Soil surface properties and plant cover play a central role on the rain water fate; they condition the prevalence of runoff or of infiltration and correlatively, the importance of soil water storage. Several authors e.g. Zhen (2006), Ye et al. (2003), Nicolau and Asensio (2000), Moreno-de las Heras et al. (2008, 2009) showed in similar areas that the presence of a plant cover tends to increase infiltration, reduce surface flow and delay erosion.

Our results showed that in semiarid areas, the hydrodynamic properties of the superficial micro-horizons determine to a large extent, the soil infiltrability and that the surface hydraulic properties are affected by degradation. Several authors like Casenave and Valentin (1989); Reynolds et al. (2007); Malam et al. (2009), Zika and Erb (2009) reported also similar conclusions. Soil degradation favors erosion (Cotler and Ortega-Larrocea, 2006; Onda et al., 2007) and consequently a progressive destruction of soils affecting dramatically their fertility (drop of the exchange capacity and of the available elements, in

particular) and the water balance (runoff increase, reduction in the available water for plants, modification of the water regime and of the soil atmosphere exchanges).

The sites installed on drying crusts are characterized by a high infiltration capacity, which facilitates the water supply of the root zone and favors the survival of the vegetation. This demonstrates that the water behavior of the studied soils is closely linked to surface features which evolves very rapidly under demographic pressure and the over exploitation of natural and environmental resources (Descroix et al., 2009; Larwanou and Saadou, 2011). Overgrazing plays an especially important role during wet periods; trampling may compact, disturb and loosen the soil surface and render it more susceptible to run-off and erosion. Indirect effects influencing dramatically infiltration and run-off may also result from a reduction of vegetation and damages caused to plants by trampling (Dunne et al., 2011).

The water behavior of the soils under study clearly illustrates one of the desertification processes related to a large extent to human and climate action. In the given area, the population growth by about 3% (INSD, 2010) results in profound changes of management techniques and the use of natural resources and rural areas. Human caused disturbances (abusive cutting of wood, poor range management, setting of bush fires, overgrazing) generate rarefaction of the vegetation, soil degradation by water and wind erosion and deterioration in soil water regime (Ganaba et al., 1998).

Previously, soils were left fallow to preserve their quality (structure and fertility), but presently they are cultivated continually. Such an overexploitation leads to soil nutrient depletion seldom compensated by addition of fertilizers. The area's climate is characterized by a high degree of rainfall irregularity in space and time. Rainfall is often preceded in June and July by heavy sand storms generating strong wind erosion which includes sand transport, deposition and remobilization. Water erosion causes removal and selective loss of fine elements, the consequence of which is the formation of erosion crusts covering large surfaces of the Sahel region. All of this led to important soil losses because of low infiltration rate and consequently high runoff rate.

CONCLUSION

This study is committed to analyzing and understanding the hydric functioning of sandy deposits of Burkinabe Sahel, in terms of physical and hydrodynamic characterization and follows up of different components of the water balance. The experiment helped to highlight a decisive influence of superficial hydraulic characteristics on the different components of the soil water balance. PZN site on erosion crust was characterized by a low infiltration capacity enhancing runoff. This is explained by the existence of a plasma film acting as a barrier. Sites placed on the drying crust (PZD) and on cultivated zone (PZC) were characterized by a good hydraulic conductivity and a high infiltration rate. PZN site was characterized by a very reduced quantity of infiltrated water relative to the contributions of rainfall and a poor water stock superficially stored (in the first forty centimeters), which promotes a quick evaporative recovery during days following rain events.

The poor recharge of soil capacity has a reduced utility for crops species. The resulting water stress explains the low vegetation density, or even its total absence, as well as difficulties encountered by vegetation to install and maintain itself. On these sites, the soil water regime is conditioned exclusively by exchanges across the soil surface. The lack of surface film indurate on the PZD and PZC sites creates conditions less favorable to infiltration, which results to a greater accumulation of water in the soil with occasionally low drainages at the depth of 70 cm.

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