# Wind processes improve water infiltration in Sahelian sandy rangeland

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**Keywords: Wind erosion, water erosion, Burkina Faso, penetrometer, Sahel**

**Abstract**

*Sandy microdunes often provide a privileged habitat for primary production of Sahelian agro-ecosystems. In degraded areas, they can also be potential starting points for the regeneration of eroded surfaces. The aim of this study was to understand the role of sandy covers in the retention of rain and runoff waters along overgrazed Sahelian hillslopes. It focuses on the interactions between wind and water processes.*

*Water can be of benefit in the development of vegetation if it is able (i) to infiltrate through crusted soil surfaces; (ii) reach a sufficient depth not to be evaporated rapidly; and (iii) to be accessible to the root system. In the present study, the wetting-front depth (WFD) was a relevant indicator that permitted to assess whether the three above criteria were satisfied. Investigations were conducted within three plots with different sizes (14,000, 376 and 36 m$^2$) and grids of observations (4 m, 0.5 m and 0.- m respectively). The largest one was a micro-catchment patched with sandy aeolian deposits. The others were distinct microdunes with a typical asymmetric shape. A cone penetrometer was used to estimate WFD and survey, its spatial variability. Soil surface conditions (micro-relief, plant cover, crusted areas) were also recorded.*

*At the catchment scale, WFD values ranged between nil and 1 meter. The deepest infiltration occurred within sandy deposits with an herbaceous cover of more than 50% (surface of the drying type) and along gullies filled with coarse sands (surface of the runoff type). Minimum WFD values were observed on bare crusted surfaces with gentle slope (surface of the erosion type). At the microdune scale, the most important depths of penetration were observed through bare windward surfaces with steep slopes. This unexpected result is attributed to wind deflation and splash erosion hampering the development of impervious crust.*

## Introduction

Dryland ecosystems develop strategies to adapt and resist adverse conditions such as drought. Naturally contracted vegetation patterns such as tiger bush is a well-known example of such strategies (Valentin *et al*., 1999). Dotted bush is another example that can frequently be found in the Sahelian zone of Burkina Faso (Leprun, 1999). Dotted bush is generally associated with sandy grassy microdunes. The genesis, development and evolution of these microdunes result from an array of factors including wind and water processes. These aeolian landforms are considered as “islets of fertility” (Thiombiano, 2000) where biomass production (Grouzis, 1991) and water infiltration (Ribolzi *et al*., 2003) are significantly higher than in other parts of the landscape. They support a primary production which is essential as a stable food supply for cattle, and are also potential initial points for the regeneration of degraded Sahelian environments.

One of the most limiting factors for natural vegetation growth within microdunes is access to water by plant root systems. It is well known that infiltration capability of Sahelian soils mainly depends on their surface features (Casenave and Valentin, 1992). The aim of this paper is to provide a better understanding of water infiltration and percolation through microdune soils. We focus on the influence of soil surface and subsurface characteristics on the spatial variability of infiltration. Water can be beneficial to the development of vegetation if it is able (i) to infiltrate through soil surfaces; (ii) to reach a sufficient depth not to be evaporated rapidly; and (iii) to be accessible to the root system. The wetting-front depth (WFD) proved

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a relevant indicator of the three above mentioned criteria. Our investigations were conducted at several spatial scales along an overgrazed hillslope in the Sahelian zone of Burkina Faso.

## Material and methods

### *Study area*

The study area is located in Northern Burkina Faso, some 13 km from Dori (UTM30, WGS84, 809,847 m East, 155,093 m North). The climate is of the Sahelian type, with a single rainy season which lasts from June to September. The average annual rainfall recorded in Dori is 512 mm. The dominant wind is the dry dust-laden Harmattan wind that blows from the northeast during the dry season and blows from the southwest during the wet season. Mean annual potential evapotranspiration, calculated by the Penman method, is about 2,396 mm. Most of the soils are solonetz soils (haplic Solonetz in the FAO terminology) developed from calco-alkaline granitic rocks.

Observations were conducted within three experimental plots of different sizes. The largest one (14,000 m$^2$) was a small catchment (BV1) composed of five main soil surface types (Figure 1a) according to the classification by Casenave and Valentin (1992): (1) bare erosion surfaces (ERO) accounted for 33.6% of the total catchment area, (2) pavement surfaces (G), which were also bare, covered 0.4% of the catchment area, (3) sedimentation surfaces (SED) covered the bottom of ponds and depressions, accounted for 1.2% of the catchment area, (4) runoff type surfaces (RUN) which mainly consisted of laminated materials of various textures deposited within rills represented 4.2% of the catchment area, and (5) the drying type surfaces (DRY), covered the leeward area of sandy microdunes represented 59.9% of the catchment area. Microdune soils accounted for 69% of the total catchment area; they supported vegetation with an herbaceous cover density exceeding 50% for about 2/3 of the total area at the high of the rainy season.

We also selected two microdunes (MD1 and MD2) for detailed investigations. MD1 and MD2 had respectively a medium (376 m$^2$) and a small (36 m$^2$) surface area. DRY was by far the dominant surface type for these plots. The soil below DRY surface was composed of two main horizons. The upper horizon (5-7 cm thick) comprised a deposit of sand with numerous macropores formed by plant roots and soil fauna. This top layer corresponded to the sand

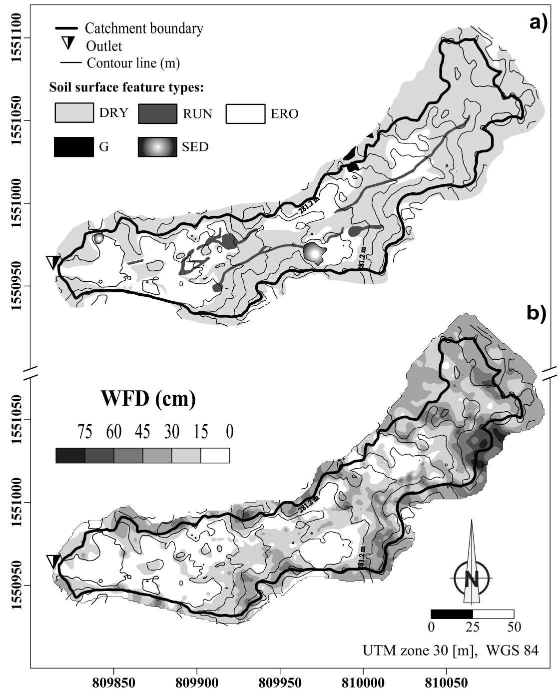


**Figure 1. Maps of the largest plot (BV1 catchment) showing a) the relief and the main soil surface features, and b) the wetting-front depth (WFD) at the height of the 1999 rainy season, one day after the 16 August 1999 rainfall event (Rainfall depth = 39 mm). Surface of the drying type (DRY); Surface of the runoff type (RUN); Surface of the erosion type (ERO); Surface of the pavement type (G); Surface of the sedimentation type (SED)**

thickness affected by cattle trampling. The total porosity of this horizon ranged between 39 and 47%, with a proportion of non-functional vesicles varying from place to place. The horizon below had a laminated structure alternating between continuous sandy and plasmic layers. This second horizon laid over a massive silty-sandy impervious horizon.

### *Topography and soil characteristics*

Topography measurements were accurately conducted on each experimental plot using an optical level. For BV1, the digital elevation model and slope gradient were estimated using a set of 1 m grid measurements covering the entire catchment (i.e. 5,890 points). For MD1, micro-relief was determined according to a 0.5 m grid (i.e. 1,484 points). For MD2, topography measurements were made every 0.1 m following an E-W transect across the microdune. We estimated surface conditions visually using the method of Casenave and Valentin (1992). Four soil pits within an adjacent microdune allowed us to estimate root density profiles within the sandy aeolian deposit.

### *Wetting-front depth*

A soil cone penetrometer was used to estimate the wetting-front depth (WFD) within the three experimental plots. The penetrometer was made up of a steel 30-deg circular cone ($ø_{base}$ = 20 mm) fastened to one end of a metallic graduated stick (ø = 15 mm, length = 1.1 m). These dimensions satisfy the standards of the American Society of Agricultural Engineers. The steel cone was inserted manually. WFD was accurate within ±1 cm of the measured value. WFD measurements within BV1 were conducted during the climax of the 1999 rainy season, one day after a rainfall event (16 August, 39 mm). Measurements covered the entire surface of the catchment and were made according to a 4-m grid (i.e. 1959 points). In MD1, WFD determinations were also conducted in 1999, but following a different rainfall event (12 July, 76 mm), which was the first and the most important event of the rainy season (rainfall depth = 39 mm). As for BV1, measurements covered the entire plot, but with finer grid of 0.5 m (i.e. 755 points). For MD2, data were performed 2 days after another rainfall event (24 June 2002, 20 mm), every 0.2 m along a representative E-W transect of 17.2 m long.

## Results and discussion

### *Influence of soil surface type at the catchment scale*

WFD within BV1 ranged between nil and 0.87 m (Figure 1b). The mean value was 0.23 m with a standard deviation of 0.17 m. This result reveals the extreme variability of infiltration within this small catchment. The zones of deeper infiltration coincide with surfaces of the drying and runoff types. In contrast, infiltration through bare crusted surfaces (ERO, G) was very limited or even nil. Figure 2 shows the median, first and third quartiles, maximum and minimum values of WFD within the main soil surface types (DRY, ERO, RUN, G and SED). The infiltration depth ranking was DRY>>RUN>ERO≈G≈SED. The difference between DRY and RUN was highly significant (threshold of significance: $\alpha$ = 0.050, Mann-Whitney unilateral test, P <0.0001) and significant between RUN and ERO (P = 0.0003). No significant difference was found between ERO and G (P = 0.108) and between G and SED (P = 0.091). Compared to DRY surface with lower vegetation cover, the surfaces with a vegetation cover of more than 50% had a significantly higher WFD values (P <0.0001).

Our results at the catchment scale clearly showed that sandy aeolian deposits had by far the highest WFD, and demonstrated the positive effect of the herbaceous cover density on water penetration depth. Microdune soils allowed a rapid and sufficiently deep infiltration so that the water did not evaporate rapidly (Karambiri, 2003) and was therefore accessible to plant roots. These results are not surprising for semi-arid areas. They confirm the influence of soil crusting (e.g. Hoogmoed *et al*., 1984) and vegetation on water infiltration in soils. It was also observed that pathways of runoff (RUN surfaces) were privileged zones where the WFD could be relatively high, particularly when concentrated runoff dissected pervious sandy aeolian deposits. This is consistent with the findings of Peugeot *et al*. (1997) who assumed significant stream bed infiltration in order to balance the hydrological budget of a small Sahelian catchment in Southwestern Niger.

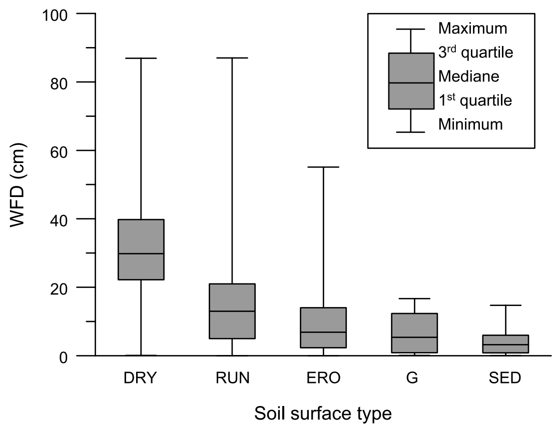


**Figure 2. Box-Whiskers plot of wetting-front depths (WFD) measured within the main soil surface features (drying-type: DRY; runoff-type: RUN; erosion-type: ERO; pavement-type: G; sedimentation type: SED) of the largest plot (BV1) at the high of the 1999 rainy season, one day after the 16 August rainfall event (Rainfall depth = 39 mm)**

### *Influence of subsurface conditions at the microdune scale*

MD1 and MD2 had similar morphological and surface features. Figure 3 shows some bio-physical characteristics and WFD along MD2. Three ERO sub-units were identified within the bare windward area. Starting at the eastern end of the microdune, the first unit was covered by a continuous erosion crust with slopes ranging between 5 to 20 degrees. The second unit, also bare, was characterised by a fragmented surface resulting from wind erosion, with a degree of fragmentation increasing with slope angle and elevation (i.e. crumbling down of the laminated structure of plasmic and sandy layers). The third unit, also exposed under the direct influence of the wind action, was located on the upper ridge of the microdune. It was a narrow fringe of grass stubble

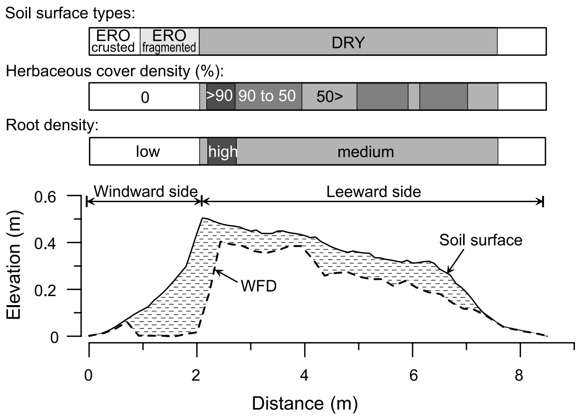


**Figure 3. Soil surface types (erosion-type: ERO; drying-type: DRY), herbaceous cover and root densities, relief and wetting-depth front (WDF) across the small microdune (MD2) measured two days after the 24 June 2002 rainfall event (Rainfall depth = 20 mm)**

(dead roots exposed at the base) dating back to the previous year. Three major soil surface units were also observed on the leeward side. The first one was a narrow sand-accumulation unit (about 50 cm wide) colonized by *Bracharia villosa*, with a cover density exceeding 90% at the high of the rainy season (Figure 3). The second soil unit was a DRY surface with a more scattered herbaceous cover. The third leeward unit was similar to the first windward one. It was bare and covered with an erosion crust. The density of live roots along the DRY surface was moderate and almost homogeneous near the soil surface (0-10 cm). In contrast, higher live root densities were found within the deeper horizons (10-40 cm) of the sand-accumulation unit colonized by *Bracharia villosa*.

In the most eastern unit (crusted ERO surface) of MD2, WFD was close to the soil surface (Figure 3). The two following windward units (steep fragmented ERO surfaces), WFD increased sharply and reached the silty-sand layer below the microdune. There, drainage was limited by this impervious layer. In the leeward side, WFD values remained high below the sand-accumulation unit with *Bracharia villosa*. Beyond this unit (i.e. drying type surfaces), WFD showed a wavy-like pattern and did not reached the impervious layer. In the last unit at the western end of the transect, the WFD was very close to the soil surface.

As for BV1 and MD2, the WFD of MD1 appeared extremely variable (Figrue 4). The minimum and the maximum values observed were 0.0 and 0.50 m respectively. The mean value was 0.22 m with a standard deviation of 0.11 m. This variability

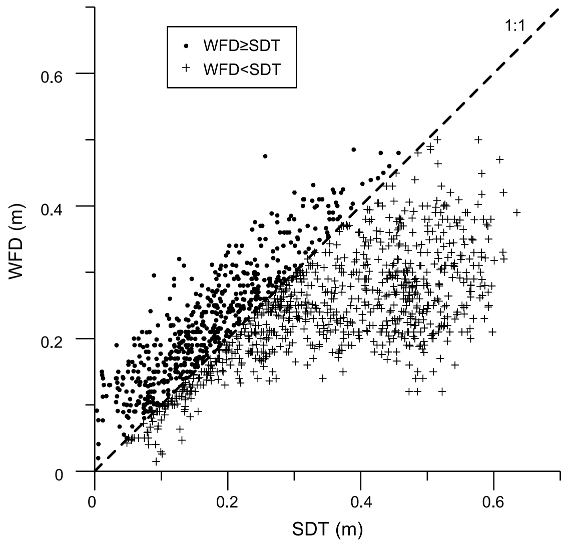


**Figure 4. Wetting-front depth (WFD) measurements as a function of sandy deposit thickness (SDT) within the medium-size microdune (MD1) one day after the 12 July 1999 rainfall event (Rainfall depth = 76 mm)**

could be related to the sand deposit thickness (SDT). Figure 4 shows the WFD measurements as a function of SDT. Two situations can be distinguished. The first situation, when WFD≥SDT, WFD and SDT were very well correlated ($r = 0.91$) and data were fitted with a linear regression ($R^2 = 0.82$). In the second situation, when WFD < SDT, the correlation coefficient between the two parameters remained high but lower than previously ($r = 0.70$). Data could not be fitted satisfactorily with a linear regression ($R^2 = 0.49$) due to the dispersion of WFD values within the areas with high SDT. To explain the dispersion of WFT for the highest SDT, we compared windward and leeward WFD values with SDT ≥0.3 m. This assessment led to the conclusion that the steep windward areas located in the eastern part of the plot had higher WFD values compared to the leeward areas (threshold of significance: $\alpha = 0.050$, Mann-Whitney unilateral test, $P < 0.0001$).

Our measurements clearly showed that the impervious horizon below the microdune controlled and limited vertical drainage. When WFD<SDT (the wetting front still did not reach the impervious horizon), our results showed an increasing dispersion of WFD with the increase of SDT (Figure 4). This wetting front dispersion might be the consequence of preferential flows resulting from heterogeneous surface or subsurface characteristics. At the soil surface level, we observed local variability: discontinuous vegetation cover characterised by micromounds of annual plants alternating with patches of bare, crusted surfaces (drying type) or of loose sand, trampled by livestock.

Uneven wetting front might also be the consequence of heterogeneous subsurface conditions due to the presence of: (i) coarse sand lenses (Boll *et al*., 1996); (ii) non-functional vesicular porosity near the surface; (iii) macroporosity caused by ant and termites activity (Léonard and Rajot, 2001); (iv) vertical shrinkage cracks. Textural interfaces are also known to force water to flow laterally (Ribolzi *et al*., 2003).

***Why was wetting-front deeper within steep windward zones?***

In the West African Sahel, convective rainstorms are often preceded by strong windstorms (Visser *et al*., 2004). During these windstorms, the steep windward side of microdunes is exposed to wind deflation: sand grains transported by wind hit the soil surface, a process through which they weaken or even fragment water-related erosion crusts (e.g. Neuman *et al*., 2005), hence improving soil water infiltrability at the onset of the rainfall event which often follows the sandstorm. During rainfall, the crumbled materials generated by wind deflation (residues of plasmic microlayer and free grains of sands) are easily removed by raindrop impacts (i.e. splash erosion). The destroyed erosion crust forms progressively again during the following rainfall event. We hypothesise that this crust reconstitution process is slower on steeper micro-slopes. Such a tendency (i.e. more infiltration on steeper slopes) was already described in tropical environments on steep loamy soils (Janeau *et al*., 2003).

Most of the time in the Sahel, rainfall is accompanied with a strong northeastern wind, which diverts raindrops from their vertical trajectory, so that windward sides of microdunes receive more rainwater per unit area and are more subjected to splash. Splash preferentially translocates soil particles downhill, which prevents the development of crusts and maintain a good water infiltrability. The previous hypothesis is still valid in the case of raindrops with a vertical trajectory. In this case, the trend for increased infiltration with slope gradient is ascribed to weaker crusting on steeper slopes: raindrops would hit the soil at a more acute angle, and thus with less vertical kinetic energy per unit area (Poesen, 1986). Lateral shearing forces due to raindrop impact might increase with slope radient, and lead to the detachment of soil particles, hampering soil crusting.

## Conclusion

Wetting-front depth measurements using a simple cone penetrometer allowed us to better understand infiltration and water storage capability in Sahelian rangelands. Our main results can be summarized according to five main points:

1. At the catchment scale, the wetting-front depth ranged from nil to 1 m. The deepest infiltration occurred within sandy aeolian deposits (drying type surface) with an herbaceous cover of more than 50%.
2. Pathways of concentrated runoff (rills) favoured water infiltration, especially when they dissected the surface of pervious sandy soils.
3. At the microdune scale, the most important penetration depths were observed in bare windward surfaces with steep slopes. This unexpected result is attributed to the combined effect of wind deflation and splash erosion which prevent the development of impervious crusts.
4. Wavy-shape water fronts observed under leeward slopes were related to soil surface characteristics; e.g. the wetting-front depth was deeper along the ridge of assymetric microdunes where sand-accumulation units colonized by *Bracharia villosa* developed.
5. Internal heterogeneities of sandy soil layers limited infiltration and/or forced the water to flow laterally: e.g. the wetting-front depth in the thinnest part of microdunes was controlled by the impervious layer below the sand deposit.

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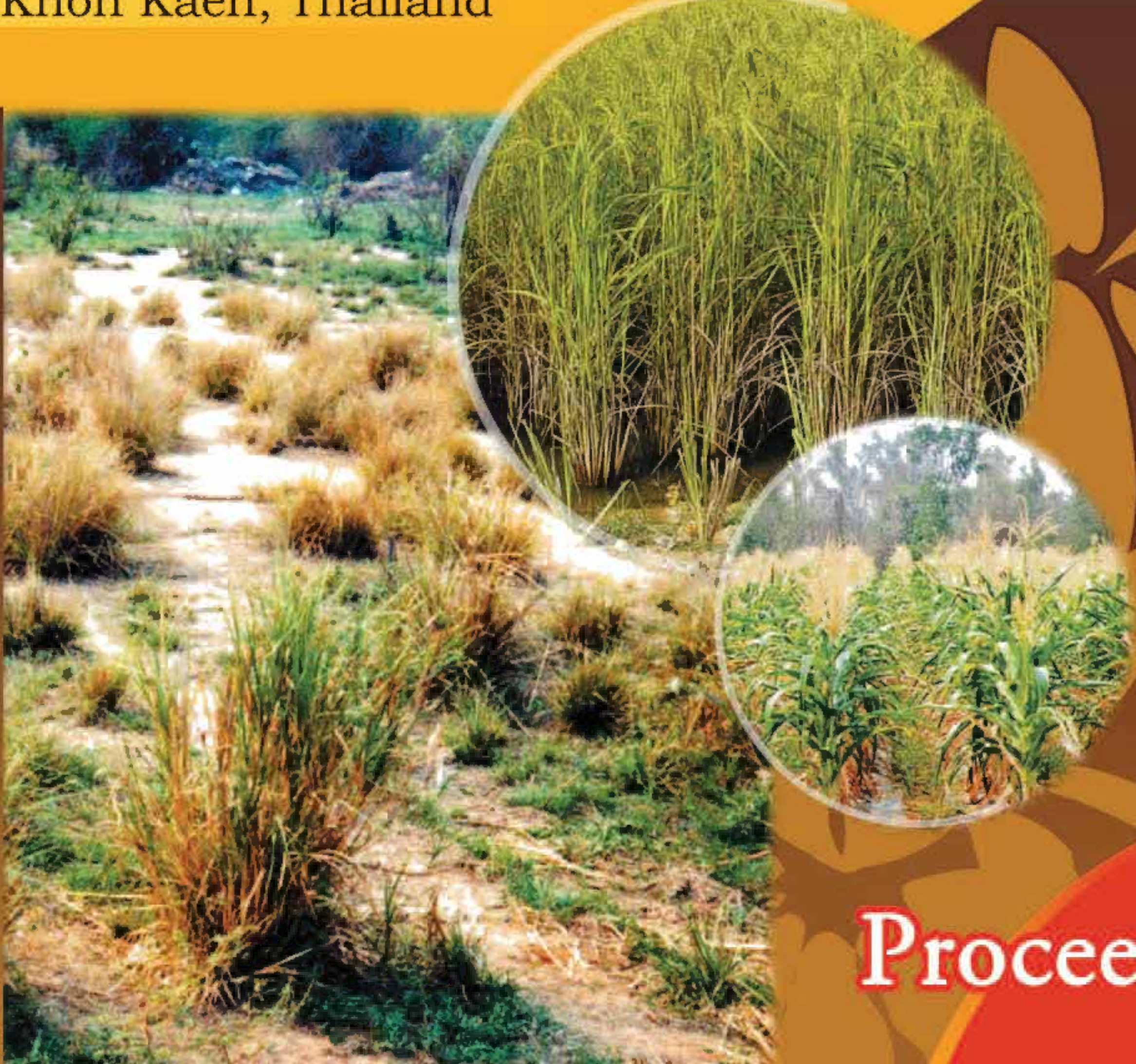

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