L'EFFET DE LA DEGRADATION DE LA SURFACE DU SOL SUR LA PRODUCTION DE RUISSELLEMENT DANS LES ZONES ARIDES ET SEMI-ARIDES DE L'AFRIQUE DE L'OUEST

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RESUME

Tout diagnostic portant sur la dégradation de l'environnement des zones arides et semi-arides de l'Afrique de l'Ouest passe nécessairement par l'approche de terrain. Celle-ci requiert une standardisation des méthodes afin de limiter les problèmes de définition et d'interprétation. C'est dans cette optique qu'est proposée une typologie, à la fois morphologique et génétique, des croûtes superficielles en vue de caractériser des surfaces unitaires types. Pour chacune de ces surfaces unitaires, de nombreuses mesures sous pluies simulées ont permis d'établir une équation d'infiltration. Cette typologie a été utilisée pour dresser des cartes d'états de surface de petits bassins versants, chaque unité cartographique étant constituée d'un ou de plusieurs types de surfaces unitaires. Ces cartes permettent de modéliser simplement la production de ruissellement à l'échelle des petits bassins versants. Des corrélations satisfaisantes ont ainsi été obtenues entre les ruissellements prévus et calculés sur sept petits bassins versants du Burkina Faso et du Niger.

Cette approche constitue une méthode simple et efficace pour établir un diagnostic de dégradation du milieu. De plus, l'identification des filiations entre les types de surfaces permet une prévision de leur évolution. Il en découle une possibilité de pronostic des modifications des régimes hydrologiques, induites par les transformations du milieu.

THE IMPACT OF SOIL SURFACE DETERIORATION ON RUNOFF PRODUCTION IN THE ARID AND SEMI-ARID ZONES OF WEST AFRICA

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ABSTRACT

The most ready way of diagnosing environmental damage in the arid and semi-arid zones of West Africa is to survey the field itself. But a systematic method is required to alleviate the problems of definition and interpretation. In this respect, a descriptive and genetic typology of surface crusts is proposed to characterize typical unit surfaces. Moreover, infiltration equation is established for each type of unit surface from simulated rainfall experiments. Since each unit surface represents a part of a mapping unit, the total amount of runoff can be evaluated on the scale of the watershed. Good correlation between the measured and calculated runoff has been obtained on seven watersheds in Burkina Faso and Niger. This system provides a simple method to assess the degree of environmental degradation and to forecast the consecutive changes of hydrological regimes.

INTRODUCTION

On semi-arid watersheds with large areas of bare or semi-bare soils, the usual models based on soil water storage do not accurately tally with reality. On these watersheds, it has been demonstrated that runoff consists mainly of overland flow caused by surface crusting (Seginer and Morin, 1970; Hoogmoed and Stroosnijder, 1984; Collinet and Valentin, 1985). Previous experience by Casenave and Valentin (1988) showed that the natural infiltration rate can be determined by realistic rainfall simulation. The results can be extrapolated to extended areas provided the concept of unit surface is used (Casenave and Valentin, this issue). The objective of this paper is to present, at various spatial scales, the efficiency of the unit surfaces typology in characterizing the changes in soil surface features due to climatic variations, population growth and land abuse and to relate environmental deterioration to decreasing rates of water intake.

CRUSTS AND UNIT SURFACES

Cultivated lands

Rapid physical processes are responsible for the formation and evolution of crusts after tillage : ploughing, hoeing, seedbed preparation, weeding,...Several types of crusts are formed in succession whilst raining. During the first stage, the clods of the soil surface are partially disaggregated and a *structural crust* is formed. In the loamy and clayey soils, it consists of one rough seal which incorporated remains of aggregates. In the sandy soils, this crust comprises two or three microlayers with the coarse particles on the top of the crust and the finer at the bottom. During the second stage, runoff is triggered as soon as the rainfall intensity excedes the infiltrability of the structural crust , *depositional crusts* are formed in the hollows of the structural crust. These consists of well-sorted layered deposits formed above the structural crust.

If we limit ourselves strictly to the morphology of the crusts, we can thus clearly distinguish different types. In the field, the extension of the different crusts varies greatly. So we can find large areas with a uniform crust but we can also find a complex jumble of different crusts. Closer analysis enables us to extract a small number of units, the repetition and combination of which recreate with reasonable accuracy the whole area observed. We call them "unit surfaces". The unit surface can include one or more types of surface crusts. In addition, grass or crop cover, as well as faunal activity (worm casts, termite mounds,...) must be taken into account. The dimensions of unit surface can vary. For practical reasons the m^2 is a useful scale and is also the usual scale for the measurement of runoff under rainfall simulation experiments.

On the scale of the unit surface, it is possible to quantify the influence of surface crusting on infiltrability using the results of the rainfall simulator experiments (Casenave and Valentin, this issue). The authors have related these stages of degradation to three major types of unit surfaces :

Cultural 1 : no crust or a unique structural micro-layer; saturated infiltration rate (Ks) = 15-25 mm h^{-1}.

Cultural 2 : one structural micro-layer combined with a non-dominant runoff depositional crust; Ks = 1-7 mm h^{-1}.

Cultural 3 : identical to cultural 2 but with high vesicular porosity in the dominant runoff depositional crust; Ks = 0-3 mm h^{-1}.

Range lands

Two main type of range lands may be discriminated according to the soils (Valentin, 1985).

On sandy and gravelly soils (fig.1)

When rainfall is sufficient, the soil surface is covered with a continuous grass layer and only little crusting occurs. During periods with rainfall of below average, plant communities collapse where moisture shortage is most severe, namely on shallow gravelly soils. Since meager amounts of organic matter make these soils very vulnerable to crusting, even under low rainfall, structural crusts develop where the vegetative cover is deficient. During the dry periods, the uppermost sandy microlayers are removed by the wind and *erosion crusts* are formed. They consist of only one rigid, thin and smooth microlayer. The winddrifted sand is entrapped by the surviving vegetation nearby. During subsequent wet periods, the rain erodes the micromounds, the bare spots are covered with the sandy washed-out sediments. As a result, seedling emergence is promoted and previously crusted and barren areas are gradually recolonized by the vegetation. Such a cyclic pattern results from the combination of several factors which may be attributed to the interactions between climate - rainfall and wind -, soil and vegetation. It is mainly observed outside the zones affected by grazing and trampling.

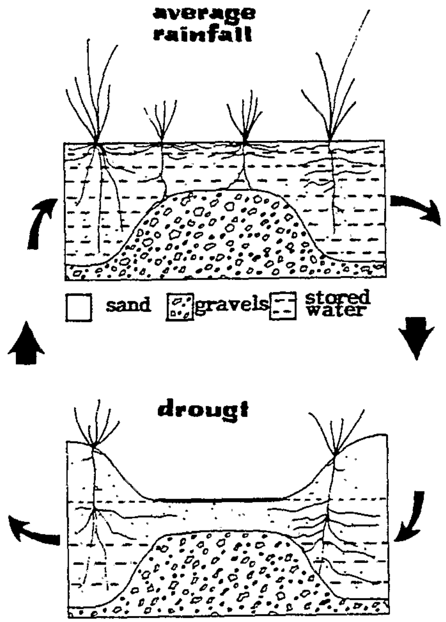
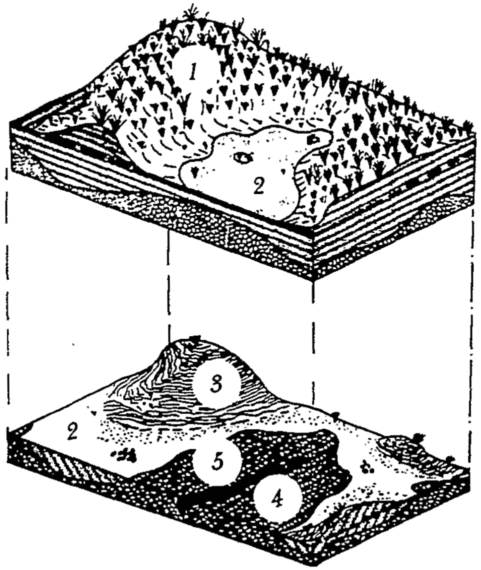


Figure 1. Schematic natural cycle of soil surface features as influenced by medium-term climatic fluctuations. (after Valentin, 1985).

On indurated soils (fig.2)

During the period of below average rainfall, these areas suffer rapidly from overgrazing since injured plant communities permit only a very low carrying capacity. As a result, the cycle is broken. Primary forms of surface degradation occur when the native vegetation disappears : the fragile *drying crust* - made of only one sandy microlayer - which covers the sandy micromounds, is eroded and replaced by *aeolian crusts*, namely sequences of thin sandy layers, weakly sealed. During a further stage of surface degradation, structural crusts in the lower parts are in turn eroded producing erosion crusts. Overland flow on these bare and crusted patches triggers sheet erosion, displayed by step-like and pedestal features. The ultimate stage of surface change occurs when the runoff water destroys the erosion crusts and also the upper horizons of the soil resulting in an outcropping of the gravelly horizon . The coarse elements cover more than 40% of the surface. The grains and gravels are embedded in an underlying seal which presents a high vesicular porosity : *Pavements crusts* are formed.



Unit surfaces :
1 - Drying , Ks = 10-20 mm h^{-1}
2 - Erosion, Ks = 0-2 mm h^{-1}
3 - Aeolian Ks = 5-10 mm h^{-1}
4 - Pavement, Ks = 0-2 mm h^{-1}

5 - Rill

Figure 2. Evolution of a Sahelian surface under the effect of drought and overgrazing. (after Casenave and Valentin, 1988).

This very impervious surface undergoes linear erosion which is fostered by livestock converting their trails to channels for rills and gullies. As shown in fig.2, great variations in runoff production are induced by such changes in surface features. The frail balance is also disturbed when the farmers extend the cultivated areas on shallow soils as sketched in fig.3.

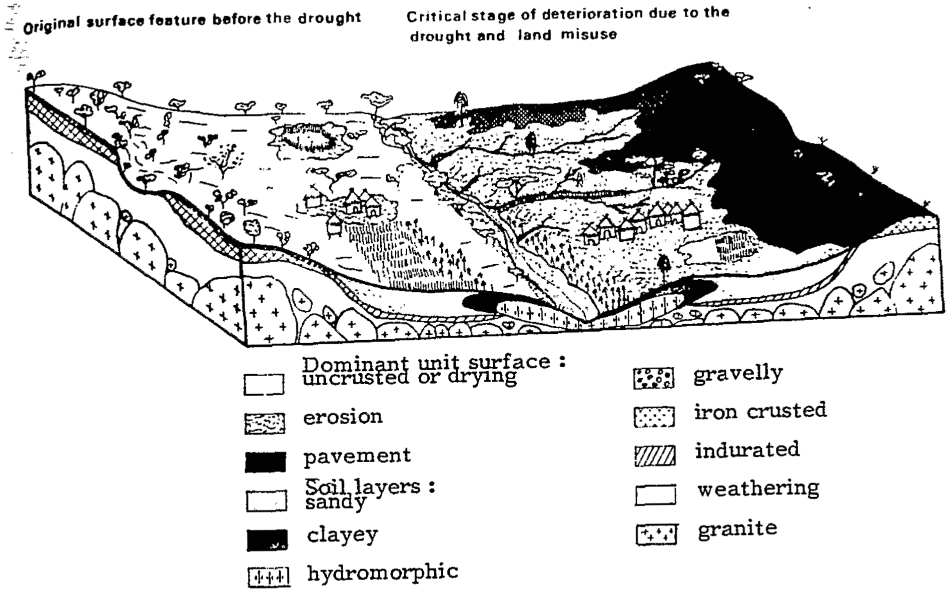


Figure 3. Block diagramm illustrating the spatial extension and the changes in surface features as influenced by drought and land misuse. Bidi, Burkina Faso.

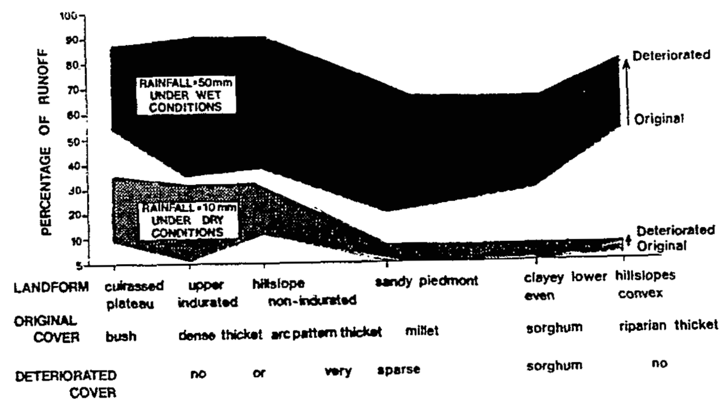


Figure 4. Changes in runoff production due to surface degradation as observed along a catena. Bidi, Burkina Faso – cf. Fig.3.

MAPPING UNITS AND WATERSHEDS

In order to characterize the state of the surface features on an extended area, for example by drawing up a map, the crust criteria would be too discriminating and the map of unit surfaces unintelligible. To alleviate this problem, mapping units must be defined. They can include one or more types of unit surfaces. Most frequently, they undergo changes over time so that the proportions of composing unit surfaces vary. For example, on a watershed located in Bidi (Burkina Faso), several mapping units have been discriminated, along an idealized catena (fig.4). Each mapping unit is characterized by the percentages of its composing unit surfaces as statistically determined from the data collected on numerous survey spots. For instance, originally the fields cropped with millet comprise one unit surface : "cultural 1" , whereas, once deteriorated, they include drying, structural, erosion and pavement unit surfaces, 23%, 25%, 42% and 10% respectively. Since the infiltration equation is known for every unit surface from the rainfall experiments, we can evaluate the amount of runoff produced by any given shower. The total amount of runoff is calculated using a simple equation where the coefficients are the respective proportions of the different unit surfaces. This system provides a simple method of determination of runoff from a given unmeasured arid or semi-arid mapping unit. As illustrated in fig.4, a low rainfall at the onset of the rainy season produces runoff only in the upper parts of the catena, mainly in the degraded zones. In the course of the rainy season, overland flow is generated throughout the toposequence by any heavy shower since the donwstream soils are almost saturated. Along degraded slopes, the velocity and the depth of the running water are increased so that further erosion is promoted.

If we combine the different amounts of the mapping units, we should be able to forecast the total amount of runoff for the whole watershed. The model which has been tested on seven watersheds of Burkina Faso and Niger provides results that were consistent with those obtained under natural rainfall (Casenave and Valentin, this issue).

Moreover, this method enables us to assess the hydrological changes and to attribute them to environmental factors. Hydrological regimes were observed on a 12.8 km^2 catchment of Burkina Faso in 1960-1962 and in 1984. Soil surface mapping involving an interpretation of aerial photographs taken in both periods showed that over less than 25 years, the cultivated land was doubled, fallow was halved, shrub savannah was decayed from 80% to 45% while severely crusted and eroded surfaces were multiplied by 20 (Albergel and Valentin, in press). Meanwhile, storm-runoff coefficients were doubled although annual rainfall has decreased by 44% (fig.5). Such dramatic changes can be imputed not only to the impact of the burgeoning population (2.6% growth per year) but also to the drought itself since the farmers extend their fields in an attempt to compensate the declining yields.

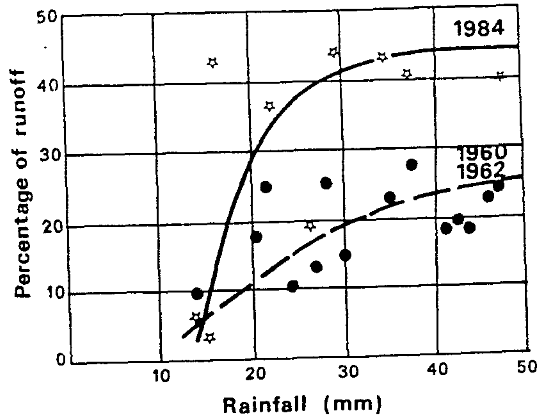


Figure 5. Variations of runoff production as influenced by expansion in cropland. Kognere-Boulsa, Burkina Faso. (after Albergel and Gioda, 1986).

CONCLUSION

Field studies using rainfall simulation can supply pertinent information regarding runoff production in the arid and semi-arid zones provided they are based on the identification of genetically related unit surfaces. The extension of this method to determine the amounts of runoff on larger scales is not a simplistic speculative exercice since it has become possible to forecast, often with considerable accuracy streamflow characteristics on several watersheds. Furthermore, this model enables the assessment of the various stages of the environmental degradation as well as the resulting changes in hydrological regimes.

REFERENCES

Albergel, J., and Gioda, A, 1986. Extension des surfaces agricoles et modification de l'écoulement. Analyse sur deux bassins de la savane africaine. XIX. Journées de l'Hydraulique, Paris, Soc. Hydrotechnique de France 1.9.1 - 1.9.6, 3 tabl., 4 fig., 18 réf.

Albergel, J., and Valentin, C., in press . "Sahélisation" d'un petit bassin versant : Boulsa-Kognere, Centre-Nord du Burkina Faso. In : Colloque Nordeste-Sahel. I.H.E.A.L. Paris.

Casenave, A., and Valentin, C., 1988. Les états de surface de la zone sahélienne. Influence sur l'infiltration. ORSTOM, Paris, 202 p.

Casenave, A., and Valentin, C., this issue. Les états de surface : une des clefs de l'hydrologie sahélienne.

Collinet, J., and Valentin, C., (1985). Evaluation of factors influencing water erosion in West Africa using rainfall simulation. in : Challenges in African Hydrology and Water Resources. IAHS Publ., n 144, pp. 451-461, 6 tabl., 3 fig., 17 réf.

Hoogmoed, W.B., and Stroosnijder, L. (1984). Crust formation on sandy soils in the Sahel. I. Rainfall and infiltration. Soil Tillage Res., 4: 5-23.

Seginer, I., and Morin, J. (1970). A model of surface crusting and infiltration of bare soils. Water Resour. Res., 6(2), 629-633.

Valentin, C., 1985. Effects of grazing and trampling on soil deterioration around recently drilled water holes in the Sahelian Zone. in : Soil Erosion and Conservation. Soil Conservation Society of America (edit.) : 51-65.