Identification of sediment sources in a small grazed Sahelian catchment, Burkina Faso

HAROUNA KARAMBIRI[1] & OLIVIER RIBOLZI[2]

1 *Ecole Inter-Etats d'Ingénieurs de l'Equipement Rural (EIER), 03 BP 7023 Ouagadougou 03, Burkina Faso*
harouna.karambiri@eieretsher.org

2 *UR ECU 049, Institut de Recherche pour le Développement (IRD), IFR Environnement et Gestion de l'Espace Régional, Bâtiment EGER, Aile C, F-78850 Thivernal Grignon, France*

Abstract The Sahelian region of Burkina Faso is currently facing serious problems of natural resource degradation, especially soil erosion, due to the aggressive climate and anthropogenic impacts. This study aimed to quantify total soil losses at the outlet of a catchment and to estimate the contribution of different sediment sources. To do this, surface water flow and associated particulate material transport were monitored for three years (1998–2000) in a small grazed catchment (1.4 ha). About 64% of the catchment is covered by permeable sandy aeolian deposits (DRY soil surface type), which support most of the vegetation, and about 34% is covered by impermeable bare soils (ERO soil surface type). To establish the contribution of the two surface soil types to the sediment load observed at the catchment outlet, several different techniques were used. These included the particle-size distribution of the sediment, clay mineralogy (kaolinite/quartz ratio) and physically-based modelling. The results indicated that the ERO surface type appeared to be the main source of sediment within the catchment.

Key words Burkina Faso; Sahel; sediment sources; soil loss; water erosion

INTRODUCTION

The Sahelian region of Burkina Faso is currently facing serious problems of natural resource degradation, especially soil erosion, due to the aggressive climate (Carbonnel & Hubert, 1992) and anthropogenic impacts (Serpentié *et al.*, 1992). This situation requires further studies to provide an improved understanding of degradation processes and to inform the development of sustainable land management strategies.

The present work forms part of a joint scientific programme involving IRD (Institut de Recherche pour le Développement, France) and INERA (Institut National de l'Environnement et de Recherche Agricole, Burkina Faso) investigating desertification in the Sahel, and aims to quantify water erosion and to study the role of different soil surface types in erosion dynamics at the small catchment scale.

MATERIALS AND METHODS

The study site, the equipment, the sampling programmes and the analytical methods have been fully documented by Karambiri (2003) and Karambiri *et al.* (2003). Here we restrict attention to key points.

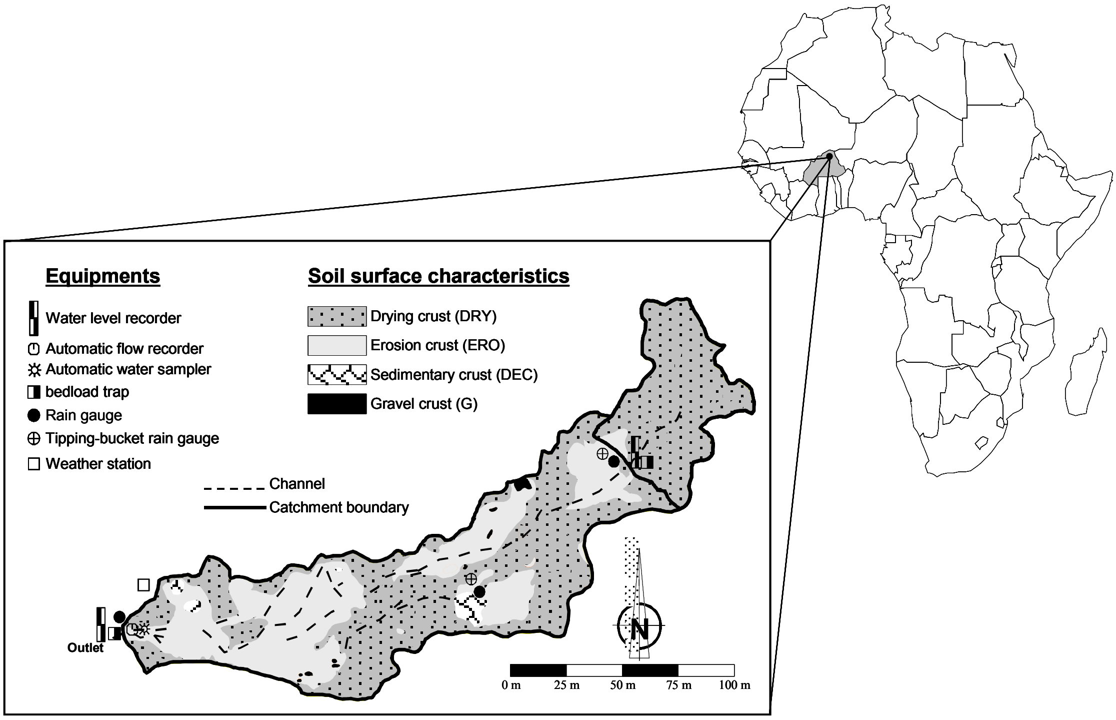

Fig. 1 Location, soil surface types and the equipment in the Katchari catchment.

The study area is located in the Sahelian zone of Burkina Faso (14°00′20″N, 00°02′50″W) close to the village of Katchari, 13 km west of Dori (Fig. 1). The mean annual rainfall is 512 mm (Casenave, 1998). The vegetation is of dry shrubby savanna type, and comprises thorny steppes with scattered acacias. It is also characterized by a discontinuous, seasonal herbaceous layer.

The study catchment is 1.4 ha in area (Fig. 1), with a relatively weak longitudinal slope (about 1%). It is composed mainly of permeable aeolian sandy deposits covered by drying crusts (DRY) (about 64%), and impermeable bare erosion crusts (ERO) (about 34%). Measurements were carried out in the rainy period and extended over three years (1998–2000). The catchment was equipped with manual raingauges, tipping-bucket raingauges, water level recorders, V-notch weirs, bedload traps, an automatic flow recorder (ISCO 4220), an automatic raingauge (ISCO 624), and an automatic water sampler (ISCO 3700s, 24 bottles) (Fig. 1). Suspended sediment samples were collected using 1-litre water samples taken at the catchment outlet at intervals of 2–5 min when the water was rising, and of 5–10 min when it was receding. The suspended-matter content was determined by weighing after oven-drying the water samples at 105°C. The bedload collected in the sediment trap after each event was air-dried and weighed.

The sediment-source sampling involved collecting samples of surface soil (the upper 0–2 cm) from representative ERO and DRY eroding areas. The grain-size distributions of the soil and sediment samples were measured using the pipette method. The mineralogy of the soil samples and the suspended sediment was determined by X-ray diffraction (Co Kα radiation) analysis of the clay fraction (0–2 μm). The runoff and erosion response of the catchment to rainfall events was simulated using a physically-based model: KINEROS2 (Smith *et al.*, 1995).

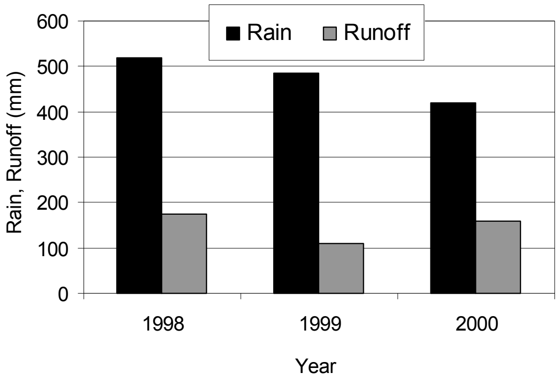

Fig. 2 Rainfall and runoff amounts recorded for the three study years.

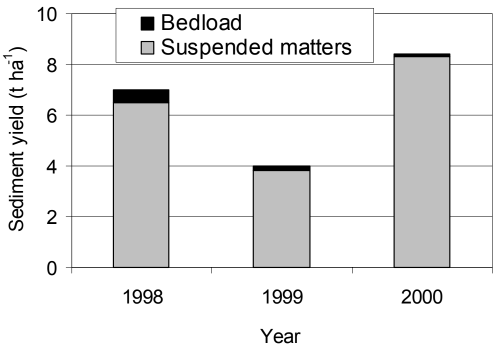

Fig. 3 Sediment yield from the catchment for the three study years.

RESULTS AND DISCUSSION

Rainfall–runoff characteristics

The annual rainfall amount was 518 mm in 1998 for 25 events, 486 mm in 1999 for 31 events and 419 mm in 2000 for 25 events. The annual runoff coefficients were 34, 23 and 38% in 1998, 1999 and 2000 respectively (Fig. 2).

Annual soil loss

The annual sediment yield measured at the catchment outlet was 6.8 t ha^{-1} in 1998, 4.0 t ha^{-1} in 1999 and 8.4 t ha^{-1} in 2000 (Fig. 3). The bedload contributed less than 10% of the total sediment yield (suspended matter + bedload). The solid transport is thus primarily in the form of suspended material. The sediment yield reached 4.2 t ha^{-1} in one flood event (10-year return period). During the study period, a small proportion (20–32%) of the floods was responsible for a large proportion (80%) of the solid transport (Karambiri *et al.*, 2003).

Seasonal variation

Seasonal variation in suspended sediment concentrations was observed. High mean concentrations (reaching 12.7 g l^{-1}) were found in June and at the beginning of July,

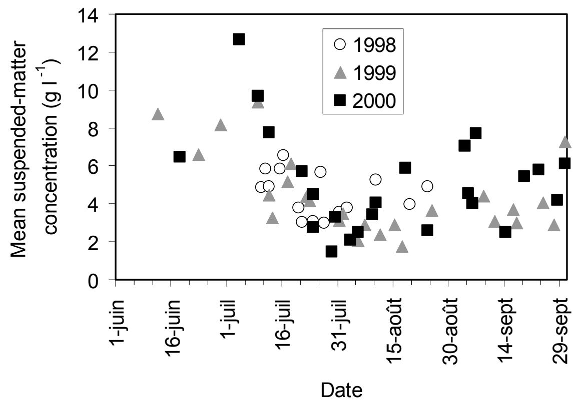

Fig. 4 Seasonal variations of the mean suspended-matter concentrations at the catchment outlet.

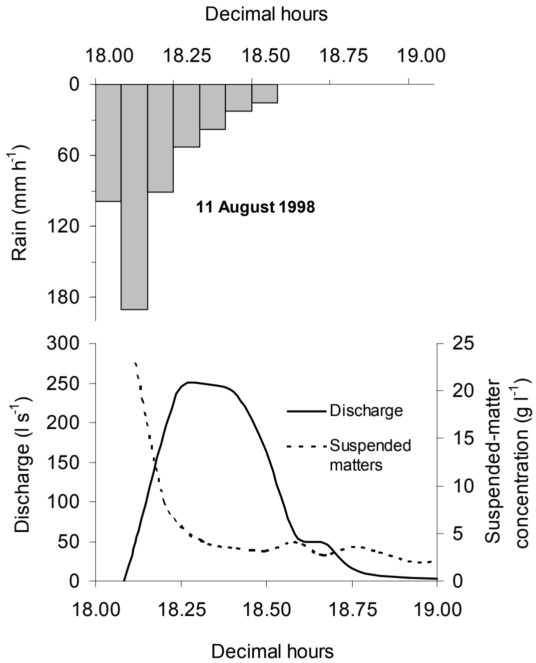

Fig. 5 Behaviour of suspended-matter during a typical annual rainfall–runoff event.

with values subsequently decreasing in July and becoming relatively stable from August to September (Fig. 4). This temporal behaviour may reflect the response of soil surfaces that have been destroyed by trampling animals (cattle, sheep and capra) during the previous long dry season, vegetation growth (increase in the protective effect of the herbaceous cover) and to a lesser extent, supply limitation (exhaustion of available dust deposits during July) (Karambiri *et al.*, 2003).

Temporal variation during a flood

An example of the variation of suspended sediment concentrations during an individual event is provided in Fig. 5. This shows: (a) very high values (23 g l^{-1}) at the beginning of the storm, (b) a marked and rapid decrease of these values during the first 15 min of the storm, and (c) stabilization at around 2.5 g l^{-1} until the end of the storm. The phase of decreasing suspended sediment concentrations corresponds to the rise in water stage and the stabilization phase corresponds to the falling stage.

The high suspended sediment concentrations are related to the condition of the soil prior to the rain. Trampling of the soil surface by animals and atmospheric deposition during the dry period separating two storms, result in dusty conditions with friable and readily transported material at the soil surface. This material is readily detached and broken up by the first raindrops, and is then transported by the first runoff. Once this potentially available sediment is eroded, the soil surface is quickly restored, limiting its mechanical deterioration (Karambiri, 2003).

The grain-size composition of sediment and the soil samples

The grain-size composition of the sediment shows that, on average, suspended sediment comprises 88% fine particles (clay and fine silt), whereas coarse particles (coarse silt, fine and coarse sand) account for, on average, 93% of the bedload (Fig. 6(a) and (b)). These observations made at the catchment outlet have been compared with the grain size composition of soil samples collected directly from the ERO and DRY crusts (Fig. 6(c) and (d)). The small proportion of fines (clay + fine silt) in DRY crusts cannot account for the great quantities of suspended sediment passing the catchment outlet; this suspended sediment is derived primarily from the ERO crusts. Both types of crusts (ERO and DRY) appear to contribute to the small quantity of bedload observed at the outlet, although the proximity of the ERO crusts to the outlet (Fig. 1) suggests that their contribution is likely to be more significant.

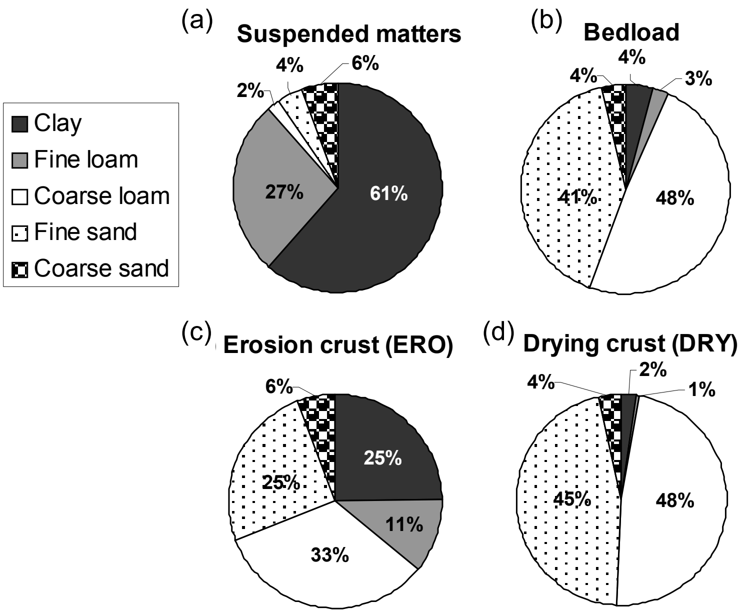

Fig. 6 Grain-size distribution of suspended-matter, bedload, ERO and DRY soil surface types.

Mineralogy of sediments and soil samples

The kaolinite/quartz (K/Q) values of the soil profiles clearly show a difference between the DRY crusts (1.5 < K/Q < 2.5) and the ERO crusts (0.5 < K/Q < 1) (Fig. 7). Variations of the mineralogical composition of the suspended clay were studied during the storm event of 11 August 1998 (Fig. 8). The clay sampled as the water was rising, has a low K/Q ratio, similar to that of the ERO crust (Fig. 8(b)). This indicates that, during the rising stage, the suspended clay comes from areas close to the outlet. The ratio reaches its maximum a few minutes after the discharge peak. The K/Q ratio is then close to that of the DRY crusts, which shows that the contribution from these

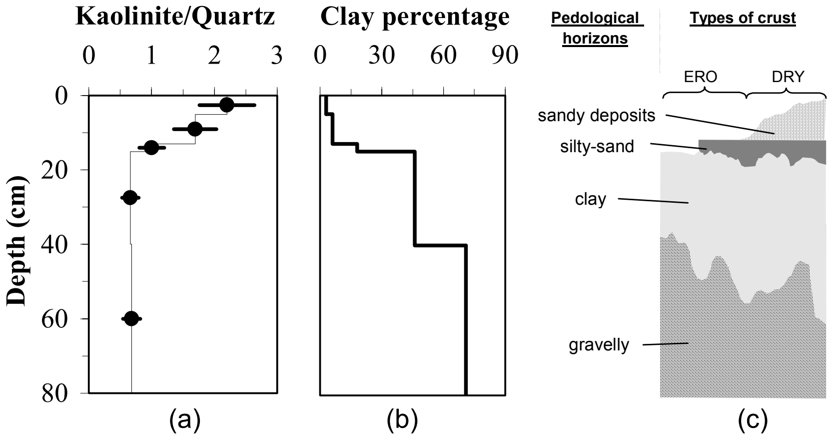

Fig. 7 Vertical distribution of: (a) kaolinite/quartz ratio, (b) clay percentage (%), and (c) pedological horizons of a representative profile (from Karambiri *et al.*, 2003).

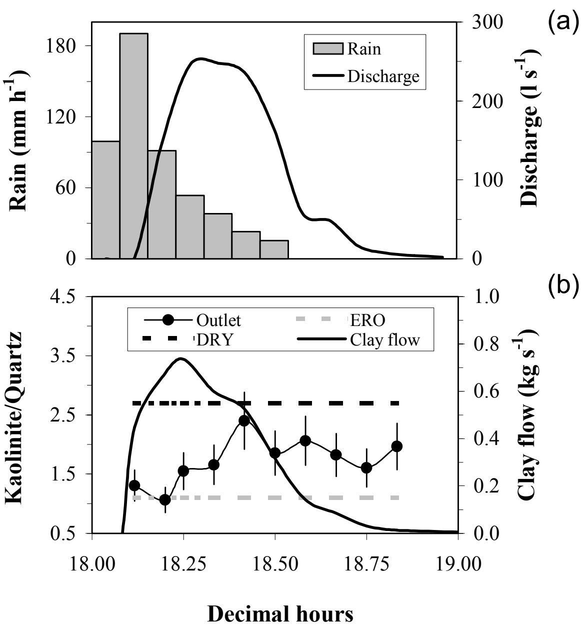

Fig. 8 Storm event of 11 August 1998: (a) hyetograph and hydrograph; (b) kaolinite/quartz ratio and clay flow of the suspended sediment collected at the catchment outlet, kaolinite/quartz ratio of the erosion (ERO) and the drying (DRY) crusts (from Karambiri *et al.*, 2003).

crusts is delayed. The increased contribution by ERO crusts during the rising stage of the flood coincides with the highest values of suspended sediment transport (Fig. 8(b)). This suggests that although these surfaces represent only 34% of the catchment area, they are the principal source of clay and suspended sediment.

MODELLING

KINEROS2 (KINEmatic Runoff and EROsion) is an event-based, physically-based runoff and erosion model (Smith *et al.*, 1995). The dynamic and distributed flow modelling in KINEROS2 is well suited to simulating hydrological and erosion processes within the Katchari catchment (Karambiri, 2003). In KINEROS2 the catchment is treated as a cascading network of surface, channel and pond elements. Channels receive flow from adjacent surfaces or upslope channels. Rectangular surfaces may be cascaded or arranged in parallel to represent complex topography or erosion features. Each element is characterized by assigning parameter values that control runoff generation and erosion processes. The flow modelling in KINEROS2 requires a temporal record of rainfall rate at one or more locations.

The Katchari catchment (Fig. 9(a)) was represented by 40 planes, 10 channels and one pond element (Fig. 9(b)). The model was first applied to the entire catchment. To estimate the contribution of the ERO-crust types to the total runoff amount at the

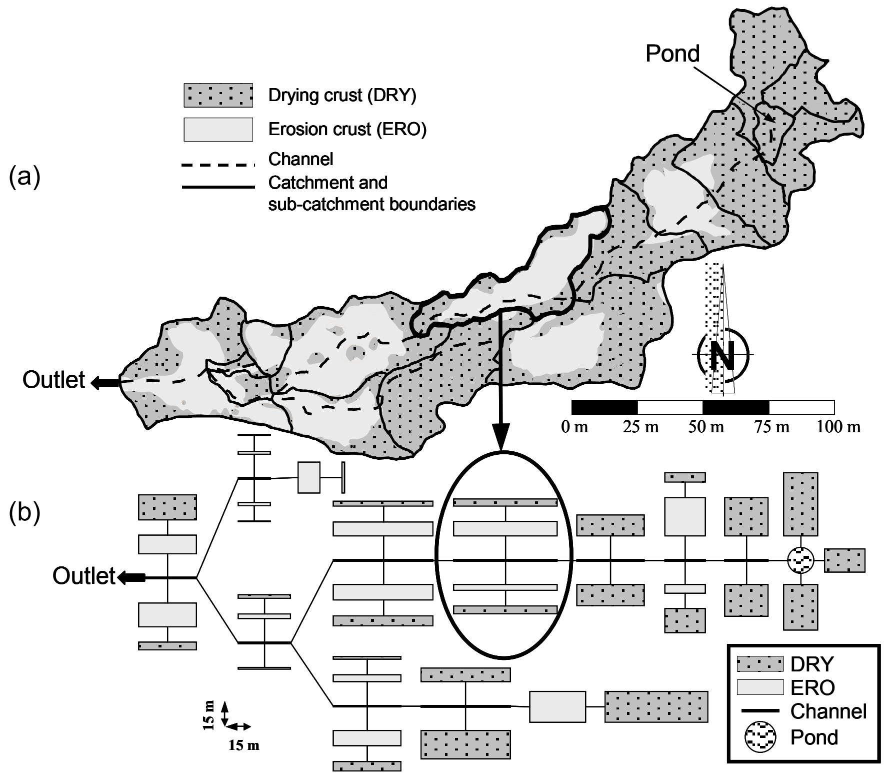

Fig. 9 (a) Division of the Katchari catchment first into hydrological sub-units and then by taking into account the soil surface characteristics; and (b) representation of the catchment by a cascade of planes and channels for the KINEROS2 model.

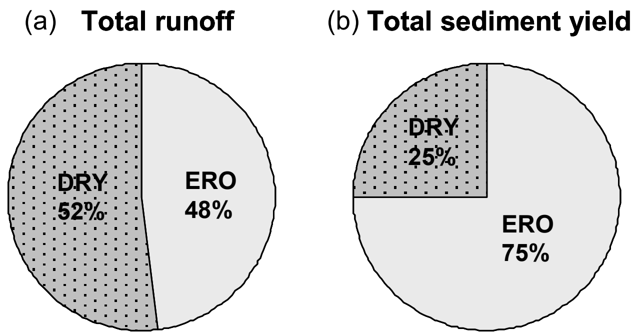

Fig. 10 Contribution of the DRY and ERO surface types for the event of 11 August 1998 to: (a) total runoff, and (b) total sediment yield (simulated by the model KINEROS2).

outlet, the model was then applied to an imaginary catchment composed only of ERO crusts. The contribution of the DRY crusts was estimated as the difference between the total runoff amount and that of the ERO crusts. For sediment transport, the contribution of the DRY surface crusts was estimated by applying the KINEROS2 model to the entire catchment and assuming zero erosion (detachment of particles) on the ERO crusts and in the channels.

The results of the simulations are illustrated by the example of the typical annual-frequency event of 11 August 1998 (Fig. 10). The ERO crusts, although representing 34% of the catchment area, contributed 48% of the total runoff and up to 75% of the sediment load simulated at the catchment outlet. These results are in agreement with those obtained qualitatively based on grain size distributions and the mineralogical analysis.

CONCLUSION

By using different approaches: sediment particle-size distribution, clay fraction mineralogy (kaolinite/quartz ratio) and physically-based modelling, this study highlighted the different roles of the two main soil surface types in accounting for the sediment load observed at the outlet of the Katchari catchment and permitted their relative contributions to this load to be estimated. The results indicated that the ERO surface crusts are the main source of sediment within the catchment. These surfaces appear to be more sensitive to erosion and play a key role in water erosion processes. As with runoff, the influence of soil profile characteristics and pedological properties on erosion processes is limited in the Sahelian zone. Such processes are exclusively controlled by the soil surface characteristics (SSC).

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