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Rehabilitation of a semiarid ecosystem in Senegal.
2. Farm-plot experiments

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Abstract

In the Sudano–Sahelian zone of western Africa, characterized by semi-extensive agriculture and subhumid climate, soil degradation and water shortages are widespread features. Soil and water conservation practices are introduced to the farmers, but often abandoned thereafter. Some interesting results have been obtained, on a hillside scale, in the southern part of the cropping basin of Senegal. As a supplement to the experimental design, two small watersheds (2.5 ha) were delineated and equipped in representative hillside locations. In 1988, both the watersheds were planned and submitted to an hydrological survey. One of them, located on a colluvial/alluvial terrace, was also submitted to soil water storage and grain yield monitoring. Results highlight a decisive effect of soil and relief features on the efficiency of conservation measures. Relevant results were obtained on the terrace, but upstream areas still generated marked soil and water losses. These phenomena, in addition to socioeconomic constraints, partly explain farmers' behaviour noticed on the hillside scale.

Keywords: Soil conservation; Runoff; Erosion; Water balance; Watershed management; Millet; Senegal

1. Introduction

In the cropping basin of Senegal, environmental degradation is found in all landscape units, as shown by high water erosion, involving sheet erosion in the upper parts of the toposequence, gully erosion at nickpoints and sand deposits in the lowland areas. For landscape rehabilitation and as a prelude to any agricultural intensification, erosion phenomena must be stabilized and runoff reduced on all slopes (Perez and Sene, 1995)

In fact, soil infiltrability increases from the upper part of the hillside to the lowland area (Perez, 1994). Thanks to this natural trend, it is possible to control overland flow by reducing its velocity and avoiding its concentration. Depending on the local conditions, this can be achieved with a network of filtering obstacles such as stone bunds or live-hedges (Lal and Stewart, 1990; Roose, 1994).

The marked tendency of the local soils to form surface seals is the result of their weak stability. These

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ferruginous loamy sands are characterized by very low clay and organic matter contents (Charreau and Nicou, 1971). Hence, there are very few solutions to increase long-term infiltrability in the soil profile. Cropping practices creating and temporarily maintaining surface roughness permit an increase surface storage and ponding time (Morin et al., 1984; Lamachère, 1991). Soil surface covers of crop canopies or residue mulches can reduce surface sealing and flow velocity (Box and Bruce, 1996). Under local conditions, it is necessary to promote rapid crop establishment and adequate canopy growth. This can be done by coupling water and organic matter management practices (Roose et al., 1992; Sessay and Stocking, 1995).

In the light of these observations, rehabilitation operations were conducted on the basis of local ecological features and human uses. The local effect of conservation measures and the mechanisms involved were studied in two small watersheds (2.5 ha), corresponding to an intermediate scale between the hillside area (1 km^2) and the experimental plot (100 m^2) and constituting a relevant sized soil unit.

The characteristics of both watersheds and the survey methods used are described, followed by the results from the hydrological survey, the water balance monitoring and the crop yield study. The discussion highlights the consequences of the results for watershed management on a hillside scale.

2. Material and methods

2.1. Watershed description

The 2.5 ha Ndiba watershed (NI) is located downslope on the colluvial/alluvial terrace. A contouring track and natural relief mark the limits of the basin. The upstream slope is nearly 0.5%, whereas it reaches 2.0% in the downstream area where rills are concentrated into a widening gully. The watershed is entirely cropped and divided into four farm plots (Fig. 1(a)).

It has a leached and disturbed ferruginous soil. The first horizon (0–60 cm depth) is sandy and friable with a continuous structure. Clay (5–10%) and organic matter (0.5%) contents are very small. Deeper, the texture gradually becomes loamy and ferric spots or gravels appear from 1.5 m depth. As a consequence of sheet erosion and colluvial deposits, the topsoil infiltrability shows high spatial variability (Perez, 1994).

In 1988, soil and water conservation practices were implemented in the NI. They included one live-hedge, established in the middle of the basin and doubled with an upstream graminae line (*Panicum maximum*), and eight filtering barriers (stone pavements and brushwood dams) across the waterways. Furthermore, several improved cropping practices were introduced into the four farm-plots: contour cultivation, dry season decompacting, shallow ridging and localized manure application. These techniques are described in Perez et al. (1997).

The 2.5 ha Yarane watershed (YA) is located in the upper part of the hillslope on the edge of the cropping area. Because of the gentle relief, the limits were delineated with an earthen ridge. The value of the regular slope is nearly 1%, with no evidence of an hydrological network, except for a downstream shallow wide waterway. Overland flow and sheet erosion characterize this area. The watershed is entirely cropped and divided into four farm-plots (Fig. 1(b)).

The soil comprises colluvial deposits and fine gravels eroded from the upper plateau. The first horizon (0–20 cm depth) is sandy (with 10% clay content) and presents 5–30% ferric gravels and the structure is continuous and fragile. Deeper, the texture rapidly becomes loamy with 50–60% ferric gravels. Below an average depth of 50 cm, ferric nodules and gravels account for 80% of the soil volume. Under dry conditions, this horizon is like a hardpan, but wetted material turns crumbly. Surface sealing is a general feature of the watershed, but the strength of the seal depends on the depth of the hardpan.

In 1988, soil and water conservation practices were implemented in the YA. They are the same as those established in the NI basin: one live-hedge, three filtering obstacles and improved cropping practices.

2.2. Hydrological survey

In 1985, the NI outlet was equipped with a rain gauge and a water stage recorder that were set up in a concrete-lined ditch. Sediment loads were manually collected from 1985 to 1992. Since 1988, 4 m^2- plots were established in different parts of the watershed (Fig. 1a) and runoff volumes measured after each rainfall event. One year after installation, filtering

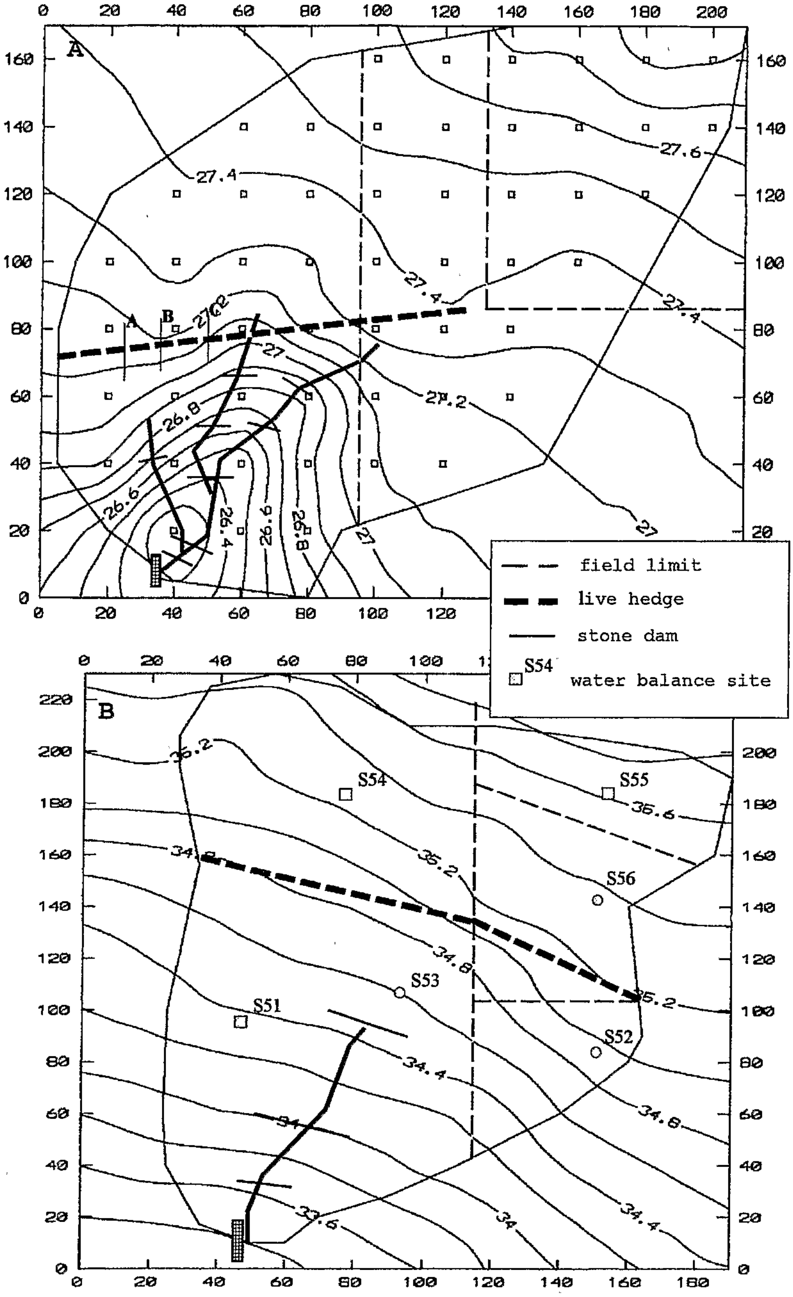

Fig. 1. Topography and developments of the two small watersheds. Soil water storage and local runoff monitoring plots are represented. (A): NI basin; (B): YA basin.

obstacles were equipped with 30 marked stakes for measuring upslope sedimentation. During the rainy season, each 10-day period, the cumulative sediment depth was estimated from the difference between the initial stake height (above the soil surface) and the actual value.

In 1986, the YA outlet was equipped with a rain gauge and a water stage recorder that were set up in a concrete-lined ditch. It is only since 1988 that the sediment loads were manually collected. Since 1988, 3 m^2-plots were established in different parts of the watershed (Fig. 1(b)) and runoff volumes were measured after each rainfall. A fourth plot was installed in an adjacent brushwood zone. As in the NI basin, 20 marked stakes were used for measuring sediment depth upstream of the filtering obstacles.

2.3. Water balance monitoring

Seven neutron probe access tubes were installed in the NI watershed, including the 4 m^2-plots, for monitoring the soil moisture. The neutron gauge was calibrated for each access tube and each specific soil layer (Perez, 1994). Measurements were done every 10-day period during the rainy season.

To strengthen the study of the soil water storage spatial variability, 53 sampling spots were located on a 20×20 m^2 grid within the NI basin (Fig. 1(a)). From 1988 to 1992, samples were obtained with a shell auger (0–150 cm depth) at the end of the rainy season. Geostatistical concepts were used for the data analysis (Burgess and Webster, 1980; Chopart and Vauclin, 1990) and the kriging procedure was used for soil water storage.

The same studies were planned in the YI. However, serious problems were encountered during the data analysis, because of the presence of gravels and nodules in the soil profile. The results were considered unreliable and therefore are not included here.

2.4. Crop yield monitoring

From 1988 to 1992, the 53 nodes of the 20×20 m^2 grid were also used for determining crop yield components and studying their spatial variability. Groundnut (*Arachis hypogea*) was harvested on 12 m^2 area plots and pearl millet (*Pennisetum tiphoïdes*) on 20 m^2 area plots. This experiment was only conducted in the NI.

3. Results

3.1. Hydrological survey

Concerning the NI basin, 129 rainfall events were recorded before watershed planning (1985–1987), 50 during 1988 – the rainiest year of the decade – and 154 after planning (1989–1992). Rain intensities were computed for all events greater then L_p=8 mm (L_p: rain depth); in this case, 67, 32 and 93 rainstorms, respectively, were analyzed for each period. Frequency distributions of rain depth (Fig. 2), maximum 10 and 30 min intensities (I_{10} and I_{30}), erosivity index (R), were the same before and after planning. It was thus possible to compare the hydrological results from both time series.

Although some flood records were lost because of the technical problems, a relevant hydrological data set was built. It contained 40 flood events before planning (1985–1987), 18 during 1988 and 36 after planning (1989–1992). Overall, the first period had a total rain depth of 2057 mm and a runoff depth of 87 mm. The final period had a total rain depth of 2340 mm and a runoff depth of 60 mm. The mean runoff coefficient thus shifted from 4.2% to 2.6% (Table 1). In fact, inter-annual variability was high during both the periods, from the occurrence of violent rainstorms, that sometimes represented upto 60% of annual levels.

Concerning rainstorms, only 31% of the events initiated runoff during the first period and 26% during the final one. Threshold values for rainfall depth (L_{plim}), maximum 10 min intensity ($I_{10\text{lim}}$) and erosivity index (R_{lim}), below which there was no runoff, were computed. When the L_{plim} value remained the same during the two periods (L_{plim}=21 mm), the $I_{10\text{lim}}$ value increased from 24 mm/h before planning to 36 mm/h after planning. In the same way, R_{lim} rose from 4.1 to 7.9 (US units). The watershed management effect was relevant but the global runoff volume savings were low.

Table 2 gives the annual hydrological results from the square-meter plots. Annual runoff coefficients ranged from 10% to 25%. During the same year, runoff depth sometimes doubled between the plots. Beyond the crop cover effects, this spatial variability was quite constant: S44 plot has the worst infiltrability. On this scale, the L_{plim} threshold values ranged from 6 to 10 mm and $I_{10\text{lim}}$ from 18 to 24 mm/h. These results indicate that the annual outlet flow represented 10–20% of the square-meter runoff estimations. This means that water distribution processes within the watershed were much higher than the losses to the outside. Similar results

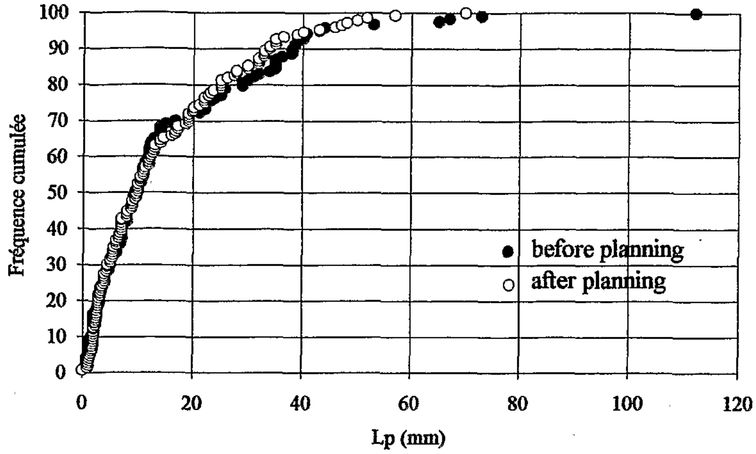

Fig. 2. Comparison of rain depth frequency distribution curves, between two periods, before (1985–1987) and after (1989–1992) planning. NI.

Table 1
Global hydrological balances of NI and YA (2.5 ha) before, during and after the year (1988) of planning

Period	No. of rains	No. of floods	Total rainfall (mm)	Total erosivity index	Total runoff (mm)	Mean runoff coefficient (%)
NI basin						
Before (1985–1987)	129	40	2057.7	900	87.1	4.2
Planning (1988)	50	18	931.5	445	40.1	4.3
After (1989–1992)	154	36	2339.7	1092	60.2	2.6
YA basin						
Before (1986–1987)	88	33	1361.4	542	159.8	11.7
Planning (1988)	49	13	917.3	434	68.3	7.4
After (1989–1992)	154	36	2282.5	1046	221.7	9.7

Table 2
Rainfall, erosivity index and annual runoff balances for 4 m^2-plots located in the NI basin

Year	Total rainfall (mm)	Erosiv. index	Annual runoff (mm)			
			S41	S43	S44	S46
1989	752.1	258	68.7	66.2	135.2	128.7
1990	488.4	247	67.0	51.9	105.1	74.5
1991	505.1	267	55.7	68.3	82.0	68.8
1992	594.1	320	85.0	96.2	159.6	69.2

were obtained in Africa by Thebe (1987); Miller (1992).

Many values were missing in the sediment load data set, because of the sampling mistakes. Only 25 relevant records were available for the first period (1985–1987) and 28 for the final one (1989–1992). Although annual balances were not feasible, variations in overall losses between the two periods were rather substantial: 13955 kg before planning and 2967 kg after planning. The same difference was noted between the most erosive events of each period: 4924 kg (July 1986; R=96 US units) before planning and 912 kg (July 1990; R=98 US units) after planning. Theoretical specific erosion thus decreased from 1.9 t/ha/year to 0.3 t/ha/year, as a result of the watershed management programme.

Concerning the YA basin, 88 rainfall events were recorded before planning (1986–1987), 49 during 1988 and 154 after planning (1989–1992). Rain intensities were computed for all events greater than L_p=8 mm; in this case, 46, 28 and 93 rainstorms, respectively, were analyzed from each period. Although the frequency distributions for rain depth were similar during both periods, maximum 10 min intensity (I_{10}) frequency curves are quite different before and after planning. Only 20% of the events had I_{10} values greater than 40 mm/h during the first period, with 55% during the final one.

The hydrological data set contains 33 flood events before planning (1986–1987), 13 during 1988 and 36 after planning (1989–1992). Overall, The first period had a total rain depth of 1361 mm and a runoff depth of 160 mm. The final period had a total rain depth value of 2285 mm and a runoff depth of 222 mm. The mean runoff coefficient thus dropped from 11.7% to 9.7% (Table 3). As in the NI basin, interannual variability was high during both the periods from the occurrence of violent rainstorms.

Threshold values for rainfall depth (L_{plim}), maximum 10 min intensity ($I_{10\mathrm{lim}}$) and erosivity index (R_{lim}), below which there is no runoff, were computed. The values were nearly steady during the two periods: L_{plim} remained the same (13 mm), $I_{10\mathrm{lim}}$ increased from 19 to 24 mm/h and R_{lim} from 2.3 to 2.7 (US units). In comparison with the NI basin, the watershed management effect was less relevant, even the global runoff volume savings were similar. The hydrological response of the YA basin was not substantially modified and there were still water losses. The cumulative runoff depth ratio (Lr(NI)/Lr(YA)) was nearly 41% during the 1986–1987 period, and dropped to 27% during the final period (1989–1992).

Table 4 gives the annual hydrological results from square-meter plots. Annual runoff coefficients ranged from 18% to 40%. As in the NI basin, spatial variability was quite constant: the S55 plot had the worst infiltrability. On this scale, the L_{plim} threshold values

Table 4
Comparison of water storage variations between two neutron probe monitoring sites

Year	Period	Water storage variation (mm)	
		S41	S47
1989	06/12 to 06/27	28	98
	06/28 to 07/11	32	77
	07/12 to 08/02	29	54
	08/02 to 08/15	25	12
	Total	114	241
1990	06/19 to 07/17	16	28
	07/18 to 07/31	29	67
	08/01 to 08/16	16	33
	08/17 to 08/31	2	36
	Total	63	164
1991	06/12 to 07/16	20	51
	07/17 to 07/31	14	13
	08/01 to 08/13	−7	−4
	08/14 to 08/27	41	118
	Total	68	178

S41 is located in the downstream part of the NI basin; S47 is located in the main gully.

Table 3
Rainfall, erosivity index and annual runoff balances for 4 m^2-plots located in the YA basin

Year	Total rainfall (mm)	Erosiv. index	Annual runoff (mm)			
			S51	S54	S55	S57
1989	740.2	254	171.7	139.7	225.6	112.1
1990	433.8	247	98.6	86.1	143.7	97.2
1991	505.6	268	128.4	102.5	198.9	110.1
1992	603.0	278	108.8	120.4	215.0	123.7

ranged from 6 to 7 mm and $I_{10\text{lim}}$ from 11 to 24 mm/h. The latter value corresponds to the fourth plot, which was in the brushwood zone. These results indicated that the annual outlet flow represented 40–50% of the square-meter runoff estimations. These proportions were higher than those issued from the colluvial/alluvial terrace plots. This is mainly because of the gentle and uniform slope, and also to the low mean soil infiltrability within the YA basin, according to Bader (1994); Torri (1996).

Although there was no sediment load data before planning, it was possible to compare the global sediment losses in the YA basin after planning, estimated to 11096 kg (25 flood events), with the NI basin losses during the same period. The global sediment load ratio (Ls(NI)/Ls(YA)) reaches nearly to 27%. Watershed management obviously had limited effects on soil stabilization of the fields located in the upstream part of the hillside.

3.2. Water balance monitoring

A distribution fitting procedure was established for each 20×20 m^2 grid data set from the NI basin. Normal distribution functions fitted all the soil water storage (0–150 cm depth) data sets, except for the year 1988 which was deleted from the subsequent geostatistical analysis. A spherical model was used to compute parameters of the normalized semi-variogram functions (Burgess and Webster, 1980). Soil water storage presents an isotropic spatial structure with a steady 50 m range value.

The kriged contour maps highlighted the same characteristic areas, even when the actual water storage values differed. The downstream confluence zone was shown to exceed the infiltration values, while the central axis zone exhibited a chronic deficit (Fig. 3). Obviously, water accumulation was the result of the relief and enhanced by filtering barriers. Further topsoil texture and soil surface feature studies, according to the method of Casenave and Valentin (1989), confirmed that the central axis zone was characterized by higher silt and very fine sand contents and unstable superficial structure (Perez, 1994). Hence, watershed management did not have a marked effect on the water storage spatial variability which, depended upon topography and soil characteristics.

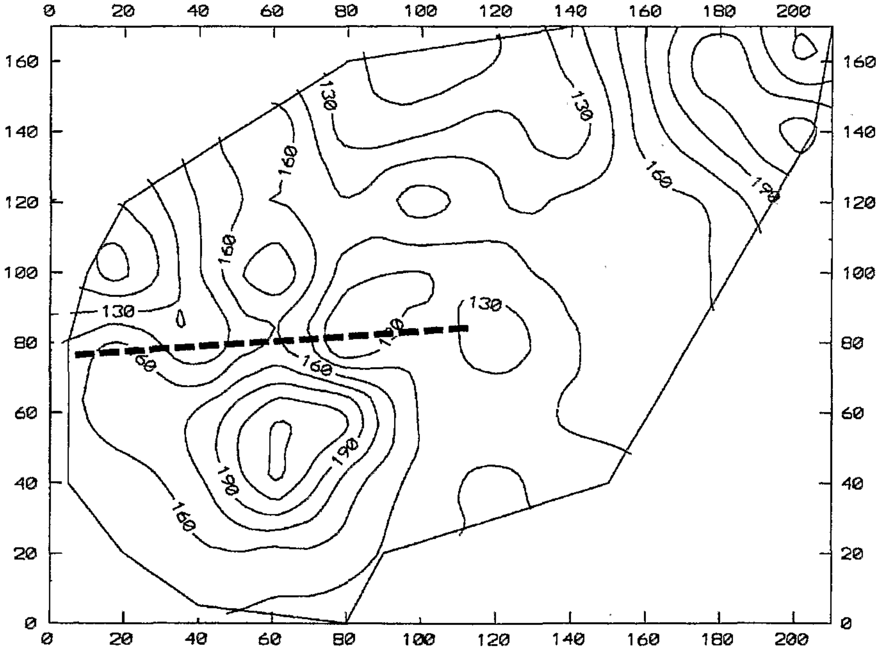

Fig. 3. Kriged contour map of the soil water storage (0–150 cm depth). NI basin, sampling grid 20×20 m^2, sampling date November 11, 1991.

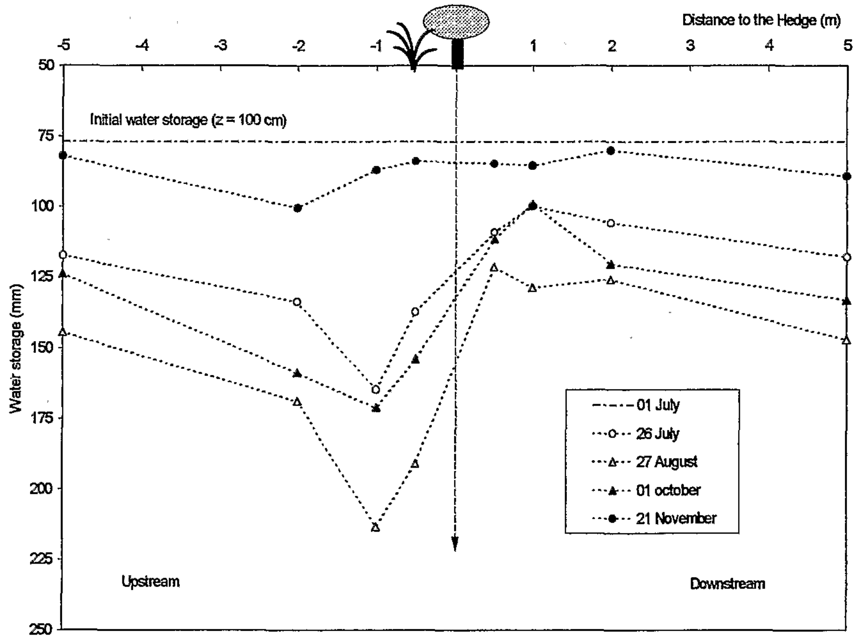

Fig. 4. Water storage variations (0–100 cm profile) along a transect perpendicular to the hedge. Four dates of measurement: 26/07/91, 27/08/91, 01/10/91, 21/11/91. NI basin.

However, some field observations partly invalidated these results, obtained at the end of the rainy season from a 20×20 m^2 sampling grid. In particular, a ponding area regularly appeared above the live-hedge, but its spatial extension was limited.

In 1991 and 1992, auger samples were thus collected along three transects perpendicular to the hedge. The sampling sites were symmetrical and located at 5 m, 2 m, 1 m and 0.5 m from the central point (Fig. 4). Sampling was carried out on a 15-day basis. Mean moisture levels at a given depth were analyzed, with transects considered as replicates. The water status was determined by dividing the space into two units:

1. the first unit refers to the cropping area on each side of the hedge, characterized by the water supply measured at the −5 m and +5 m abscissae; the mean runoff depths from S41 and S43 square-meter plots were subtracted from the daily precipitation;
2. the second unit refers to the hedge, characterized by the water supply measured at the ±0.5 m and ±1 m abscissae; the live-hedge evapotranspiration was determined from periods without runoff and compared to that of the crops defined above. A ratio of 1.3 was thus obtained in favour of the hedge; it was applied thereafter for all situations.

At the beginning of the rainy season, the infiltration gain above the hedge was around 118 mm in 1991 and 84 mm in 1992. In 1991, global water storage variations, measured at the end of the rainy season, were in line with the first infiltration gains. However, for 1992, a simple study of global water storage variations did not highlight the filtering role of the hedge. The infiltration gain mainly met the needs of the shrubs and Graminae species at the end of the season. Moreover, marked stake monitoring enabled assessment of annual sedimentation upstream from the hedge. This sedimentation was found to be about 1.8 cm/year after installation of the hedge, and levelled off at about 0.5 cm/year thereafter.

Concerning the filtering barriers, from 1989 to 1992, a comparison was made between water storage values from the S47 neutron probe access tube, located in the main gully and the S41 and S42 water storage values (Fig. 1(a)). Soil water storage could be com-

Table 5
Grain yields for a pearl millet (var. SOUNA III) cropped in the NI basin in 1988, 1990 and 1992 (millet/groundnut rotation)

	Location	Grain yield (kg/ha)		
		Mean	SD	Coefficient of variation (%)
1988	Upstream	1143	397	34.7
	Downstream	897	388	43.3
1990	Upstream	915	239	26.1
	Downstream	635	250	39.4
1992	Upstream	816	52	30.1
	Downstream	1177	419	35.6

Variations due to the location, relative to the live-hedge position. Harvest spots: 20 m^2.

puted on a per-year basis until the last measurement level (250 cm depth) was reached by the wetting front. In fact, this was not a major constraint as most of the surface runoff was trapped at the beginning of the rainy season, when crop cover was sparse and violent rainstorms occurred. During the monitoring period, infiltration gains within the gully ranged from 101 to 127 mm (Table 5). The mean sedimentation above the filtering barriers was found to be about 16 mm/year after installation, and levelled off at 13 mm/year thereafter. These confirm former results obtained by Ruelle et al. (1990).

3.3. Crop yield monitoring

The effect of the improved cropping practices on soil and water management and then on the yield components were studied separately (Perez et al., 1996). The field survey within the NI basin highlighted the spatial variability in the crop response to the soil and water conservation measures. Before planning, the downstream widening gully was undergoing erosion and topsoil crusting. Some 2500 m^2 were progressively abandoned by the farmer, but in 1988 the entire area was cropped, because of the sediment deposits above the filtering barriers and dry season soil decompacting.

As two plots were under an alternate crop rotation (S44 and S46 locations), rather than carrying out a geostatistical analysis the remaining area was divided into two blocks relative to the location of the live-hedge: upstream (13 spots) and downstream (11 spots) part, belonging to the same farmer.

Table 5 gives the results of the grain yield variations recorded in 1988, 1990 and 1992 with a pearl millet (var. Souna III) crop. The production level was high in comparison to nearby fields (Perez et al., 1997). This was partly because of the soil characteristics but also to the current adoption of improved techniques by the farmer. The downstream area reached the same potential as the upper part. Even though annual climatic variations interfered with evaluation of the agricultural results, local farmers stressed the fact that the surface savings and field homogeneity were two relevant benefits.

4. Discussion

According to Amir (1996), soil rehabilitation attempts are dependent on the existing climatic conditions, cropping systems and the socioeconomic environment. In the case of western Africa, with semi-extensive agriculture and subhumid climate, few technical references are available, even though many extension programs have developed these soil and water conservation practices. Serpentie and Lamachere (1990) improved water infiltration by combining soil ploughing and stone bunds, in 1000 m^2 plots located in northern Burkina Faso. In the same country, Van Duijn et al. (1994) confirmed the advantage of stone bunds for water management in the local food crop system. Most authors acknowledge that the crop response is often moderate because of subsequent leaching processes or unbalanced water and mineral supply (Reyniers and Forest, 1990).

The NI, located on the colluvial/alluvial terrace, is characterized by a good soil infiltrability and a downstream gully system. Before planning, the annual runoff coefficient was low (4.2%) and corresponded to a marked water deficit between the square-meter runoff potential and the outlet flow. Overall, despite the low absolute values, watershed management allowed a reduction of 40% in water losses, and sediment loads were six times lower. Within the watershed, water distribution was not greatly modified according to the water storage spatial variability.

However, limited areas located above the filtering barriers, concentrated water infiltration and trapped sediments. Consequently, the topography and soil surface features of the downstream zone were considerably modified. These improvements, associated with the new tillage techniques and manure application, favoured sustainable cropping of the entire area.

The YA, located in the upper part of the hillside, is characterized by a low soil infiltrability and a uniform relief. Before planning, the annual runoff coefficient was nearly 12% and represented 40% of the square-meter runoff potential. After planning, water and soil losses remained high. Obviously, the filtering effect of the conservation measures was not efficient enough. The absence of a well identified drainage net led to the creation of large fluctuating waterways. Surface runoff thus bypassed the filtering barriers and sediment deposits were small (live-hedge: 0.5 cm/year; filtering barriers: 1.0 cm/year).

Moreover, because of the soil constraints, improved cropping practices were less efficient than applied on the colluvial/ alluvial terrace. For exemple, dry season decompacting created 10 cm deep subsoiling in the downslope sandy soils but only 7 cm deep in the upslope gravelly soils. Soil surface features also changed more rapidly under raindrop impact (Perez, 1994).

5. Conclusion

On a farm-plot scale, the two experimental watersheds were representative of the local environmental constraints and the land use features. The poor quality and the crusting tendency of upslope soils were not favourable for the establishment of crops or young shrubs. Greater effort was also required from the oxen for soil tillage. Often far from the village and rented to outsiders, the fields located on these soils are not priorities for farmers. In contrast, downslope soils, deep and easy to till, allow rapid development, because of surface savings and the high yield potential.

In the light of these phenomena, reinforced by the different technical results described in this paper, the natural trend will probably lead to the developed belts located along the lowland axes and topped by degraded hillsides. This tendency could explain the behaviour of farmers described in Perez et al. (1997). Although developing hillsides requires collective work, the same people, as individual farmers, were observed slashing the upper rangelands while neglecting improved cropping practices, except for the most productive fields.

This is the paradox of watershed management in the southern part of the cropping basin of Senegal: although the overall degradation processes along the hillside require top–down reclaimation, social constraints lead to a bottom–up organization.

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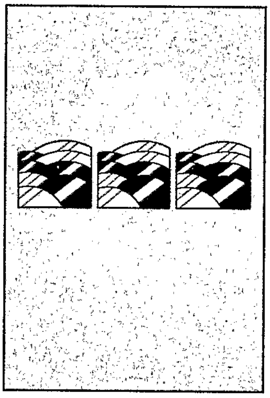

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