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Rehabilitation of a. semiarid ecosystem in Senegal
1. Experiments at the hillside scale

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Abstract

The groundnut cropping basin of Senegal suffers environmental degradation, with a negative impact on local agriculture, shown by intense soil erosion. Despite the existence of many extensive programmes, there are few results concerning actual effects, at the hillside scale, of rehabilitation practices. The object of the study, carried out from 1983 to 1993, was to give evidence of the actual effects, in terms of hydrology and agronomy, of conservation measures set-up in a small cultivated watershed (60 ha). The measures included, on the basis of ecological features and human uses, live-hedges, stone bunds and improved cropping practices. The hydrological survey, based upon the paired watershed technique, gives evidence of land conservation, rather than land restoration, due to these developments. The efficiency of the hedges is mainly due to the favourable planting conditions. The proposed cropping practices were adopted by farmers to varying degrees, and field monitoring showed no actual effect on average crop production. To improve the cost/benefit ratio, the scientific staff should have emphasized, for the attention of the farmers, the necessary linkage between fertility restoration and runoff control. Despite this limitation, an increasing number of farmers and village communities are asking for technical assistance. © 1997 Elsevier Science B.V.

Keywords: Watershed management; Cropping practices; Paired watershed technique; Runoff; Senegal

1. Introduction

In Africa, environmental degradation is now well documented (Pieri, 1989; Richard. 1990; Poulsen and Lawesson, 1991) and characterized by intense soil erosion, soil fertility loss and marked reductions in plant cover. Natural (mainly climatic) factors and anthropic factors are considered to be jointly responsible for this phenomenon (Le Borgne, 1990; Sircoulon, 1992; Grouzis and Albergel, 1989; Lericollais, 1990).

The agricultural capacity of lands in the Sudano-Sahelian zone is reduced by this ecosystem degradation. with a consequent negative impact on local inhabitants. Ecosystems have to be restored in order to assure sustainable socioeconomic activity in the zone. Extensive programmes have been set up to control land degradation, but they often fail because they are conducted on a strictly technical basis, without addressing the widespread problem

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(Rochette, 1989; Tybirk, 1991). Moreover, there are very few results concerning actual effects, at the hillside scale, of land management on crop production improvement or soil and water conservation (Lal and Stewart, 1990; Vlaar, 1992).

The present study was carried out in the groundnut cropping basin of Senegal from 1983 ta 1993. This region supplies almost half of the groundnut and millet produced in the country. In the light of the diverse: activities and interactions that occur in rural areas, our rehabilitation operations were conducted on the basis of ecological features and human uses (Perez and Sene, 1995). The' objective was to give evidence of the actual effects, in terms of hydrology and agronomy, of rehabilitation practices used in a small cultivated watershed (60 ha).

We first review the features of the zone and techniques used for watershed management and survey. Next. we present results from the hydrological survey, the hedges and field monitoring. Discussion emphasizes the cost/benefit balance of such land management for farmers.

2. Material and methods

2.1. Area description

The study area (Fig. 1) has a Sudano-Sahelian climate marked by a long dry season (7 to 9 months) and a short summer rainy season (3 to 5 months). The mean annual precipitation for the 1930 to 1990 period was around 820 mm. and dropped to 661 mm over the last two decades (1970 to 1990). Despite this rainfall deficit, violent rainstorms have occurred regularly (Dacosta, 1992).

The region is characterized by a series of vast tablelands (30 to 60 m elevation), interlaced with a network of valleys with gradual slopes. In the central plateau area, the soils are ferruginous without hardpan. Formerly densely wooded savannas, these lands have been cleared. Only talus is now covered with quite poor brushwood, mainly *Combretaceae* species (Bertrand, 1972).

At the base, the hillslope includes an upstream slope and a vast terrace. On the slope, there are quite primitive soils, colluvial deposits, with fine gravel and ferric hardpan. These soils, which were recently cleared, degrade very quickly after cropping: The ter-race has leached, disturbed ferruginous soils on colluvial/alluvial deposits. This is the traditional area of human occupancy. There has been a sharp drop in soil fertility in recent years induced by continuous cropping and fertiliser and manure shortage (Ange, 1991).

In the lowlands, the soils are quite primitive hydromorphic alluvial deposits, colonized by *Acacia seyal* and *Mitragyna inermis*. The main factors limiting agricultural development are violent floods and sand buildup due to erosion on the hillslopes (Albergel and Perez, 1993).

The population density was estimated. in 1983, at 61 inhabitants/km^2: this population (mainly Wolofs) has almost doubled over the past 10 years. The local farming system is chiefly based on groundnut (*Arachis hypogea*) and millet (*Pennisetum tiphoïdes*), with a trend towards combining agriculture and livestock production. From 1970 to 1990. cropping areas increased from 40% to 70% of the total surface. They are now characterized by continuous cultivation and animal draught (Sene and Perez. 1994).

2.2. Methods and techniques

2.2.1. Paired watershed technique

In 1983. two watersheds were delimited in the Rural Community of Kaymor. Though two cases absolutely alike could not be found. we stressed similarity of geomorphological and land occupancy characteristics. The outlets were five kilometers apart. located close by villages to facilitate hydrological surveys. The two basins were studied under natural conditions over an initial period (1983 to 1987) and then conservation measures were set up on one of them in 1988. From 1989 to 1993, we studied the hydrological result of these soil conservation practices, in comparison with the traditional land use. This paired watershed technique (Bosch and Hewlett, 1982; Fritsch, 1992) is based on the built-in assumption that other factors are nearly constant.

The Ndierguene watershed (ND), of 0.9 km', presents a shallow relief (relief/length ratio = 5.7 m/km). The tributaries, mainly tracks and ephemeral gullies, feed temporarily the downstream channel during the rainy season (June to October). In 1983, the cropping area represented 42% of the basin area (Fig. 2a). The outlet is equiped with a rain gauge and a water-stage recorder located in a concrete-lined ditch. From 1983 to 1985, suspended sediments were collected with an automatic sampler. Afterwards, due to a weak reliability of resuhs, sediments were manually sampled. The ND catchment is considered as a control basin during the whole period.

The Keur Dianko watershed (KD), of 0.6 km^2, is situated on the same hillside. It presents a more elongated shape and a more distinct relief (relief/length ratio = 12.4 m/km) than the former one. In 1983, the cropping area represented 34% of the basin area (Fig. 2b). The outlet equipment is identical to the previous one. Unfortunately, suspended sediments were not manually sampled until

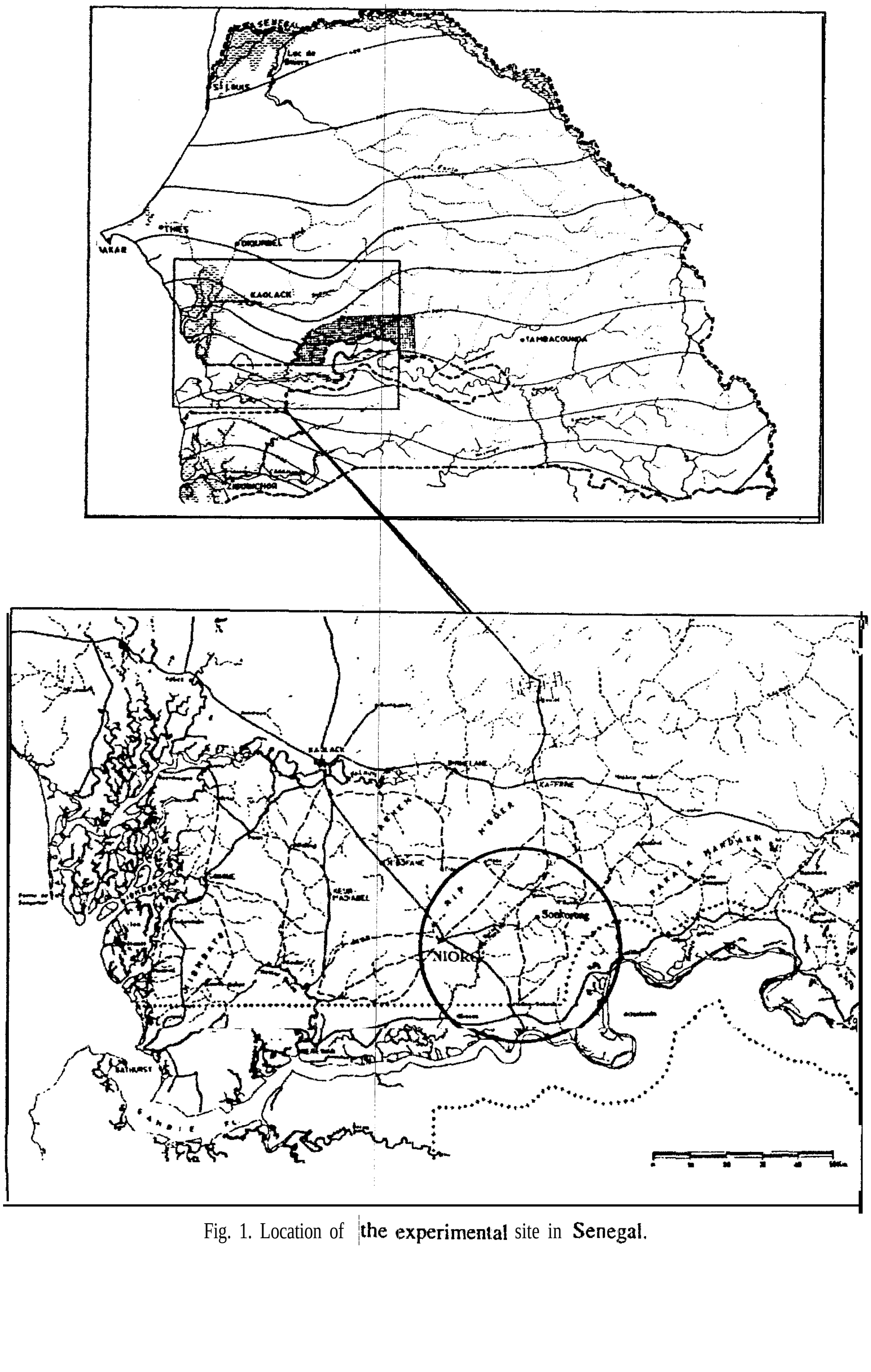

Fig. 1. Location of the experimental site in Senegal.

1988. Conservation measures started in 1988, so we can consider a first period of five years (1983 to 1987) for original conditions and a second one (1989 to 1993), for soif and water conservation.

2.2.2. Soil and water conservation pracfices

Land degradation was found in both watersheds. Intense runoff and sheet erosion characterized upstream areas, with gully erosion and sand deposits in the downstream areas. As generally accepted, we thought that management that alleviated these constraints would have an impact on crop yields and rangeland productivities (Lal and Stewart, 1990; Pierce, 1991). So, we began, from 1988, to introduce soil and water conservation practices to the farmers working in the Keur Dianko watershed (Fig. 3).

First, we tried to partition hillside area in order to efficiently deal with runoff and concentrated flow and so, to reduce erosion process. In the cropping area 13 live-hedges, covering a total of 4000 linear meters, were set up by villagers between 1988 and 1990. Multiple shrub species were planted to insure the best on-site selection, according to soil conditions and farmers remarks: *Acacia nilotica, Bauhinia*

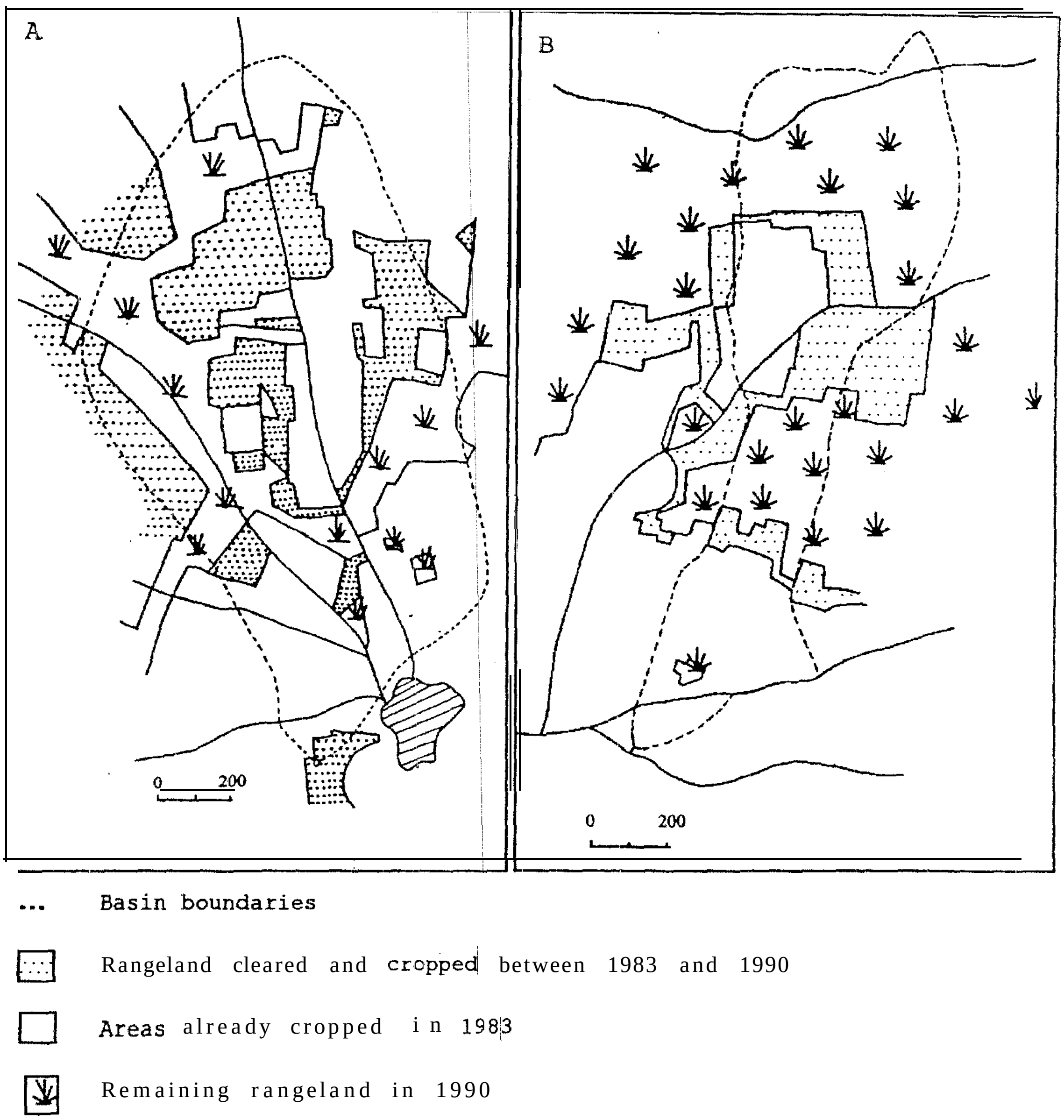

Fig. 2. Land use evolution within the two watersheds, between 1983 and 1990. (A): Control basin; (B): Developed basin.

rufescens, Piliostigma* reticulata, *Ziziphus maurita-nia, Prosopis julifora, Acacia seyal, Acacia mellif-era, Dichrostachys glomerata (Rautureau et al., 1991). The hedge spacing, due to the shallow slope and the absence of suitable formula, was based opon the field pattem and the landowners agreement. Planting techniques were described by Ruelle et al. (1990). To decreast: runoff energy at the base of the

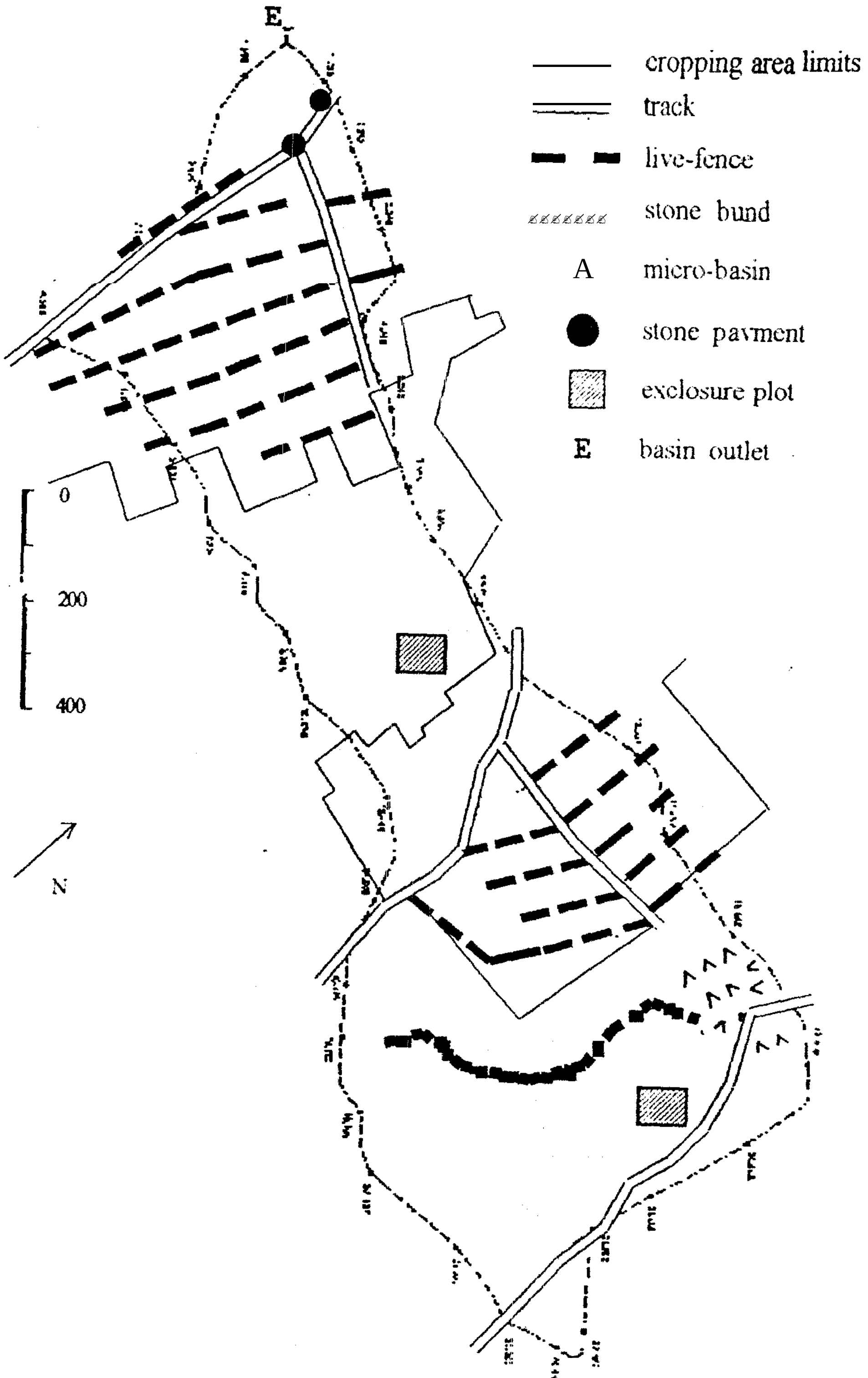

Fig. 3. Watershed management plan of the Keur Dianko basin (0.6 km').

talus, a stone line was constructed in a brushwood zone with material available on the site.

Then, inside this network, we tried to increase infiltration and water storage in the soil using the techniques adapted to traditional rangelands or cropping areas. Hence, two exclosure plots (0.5 ha) were located in the rangelands to furtber natural vegetation renovation (Diatta, 1994). On the edge of the talus, some microbasins planted to shrub species (*Acacia nilotica, Bauhinia rufescens, Ziziphus mauritiana*) permitted the revegetation of degraded areas with outcroping hardpan. In the crop fields, the following cropping practices were proposed to farmers:

- Contour cultivation.
- Dry season decompacting. This technique corresponds to a 10 cm deep subsoiling done by animal traction with a single excavating pick. Because there is no available time during the beginning of the rainy season (seeding operations), it is the only solution to help infiltration of water from the first, and often violent rainstorms (Le Thiec and Bordet, 1990; Seine and Perez, 1994).
- Shallow ridging before emergence, for groundnut crop. It is a slight modification of the traditional weeding being practiced just after seeding. Some rags are placed over the heads of the local hoe. This is a clever and not expensive way to increase soil relief on the seeding line (5 cm high). This technique can also be combineci with a localized manure application (Sene, 1995).
- Shallow earthing up, for millet crop. When the crop begins to develop suckers a small ridger is used to create mounds on the seeding line (10 cm high). As above, it can be combined with a localized manure application (Perez et al., 1996).

At last, brushwood checkdams and stone pavments were used to stabilize the main gully and transform it in a permanent waterway and, therefore, secure the adjacent track. This work was done by villagers.

2.2.3. *Field and hedge monitoring*

The local impact of individual conservation measures (live-hedge, stone line, cropping practices) and the mechanisms involved were not studied at the hillside scale. They were taken into account during farm plot scale experiments, described further in another paper (Perez et al., 1996).

Beyond the hydrological response to the watershed management, we were also interested in , long-term survey of the crop yields. For this purpose. an exhaustive field monitoring was realized, since 1987, in the Keur Dianko watershed. Because of time consuming this survey could not be achieved in the second watershed, except for the cadastal survey The monitoring comprised for each of the 6’7 field plots:

- Annual cadastral survey.
- Recording the dates of farming practices and the types of tools
- Observations of weeding levels, crop emergence and flowering.
- Measurements of yield components from 25 m² sampling plots.

The object of the hedge monitoring was to estimate, according to soif and rain conditions, the average rates of survival and grouth for each species This was important for explaining farmer’s motivation and for planning shrub pruning. Twice a year (June and October) each of the 7000 plants was controlled and measured (Rautureau et al., 1991).

3. Hesults

3.1. *Hydrological survey*

Comparison of the annual hydrological balances of the two watersheds shows similar runoff coefficients before applying consenation measures in Keur Dianko (Table 1). During the period from 1983 to 1987, cumulative runoff totalizes 54.7 mm in Keur Dianko and 72.6 mm in Ndierguene watershed. The average runoff coefficients were close: 2.1% (KD) and 2.6% (ND).

After 1988. the annual hydrological balance of the Ndierguene watershed notably evolved, as shown by a marked increase in flooding; this contrasts with the stabilizing trend noted for the Keur Dianko watershed (Table 1). During the period from 1989 to 1993, cumulative runoff was 87.9 mm in Keur Dianko and 277.8 mm in Ndierguene watershed. The average runoff coefficients were distinct: 2.9% (KD) and 7.0% (ND).

As shown in the Fig. 4, this difference can’t be attributed to any major variation between the two

Table 1
Comparison of the annual hydrological balances between the pilot basin (ND; 90 ha) and the developed basin (KD; 60 ha)

Period	Year	ND basin			KD basin		
		Annual rain (mm)	Annual runoff (mm)	Runoff coefficient (%)	Annual rain (mm)	Annual runoff (mm)	Runoff coefficient (%)
Before	1983	429.2	3.1	0.7	391.4	6.8	1.7
	1984	420.8	7.8	1.9	354.6	6.7	1.9
	1985	493.1	14.3	2.9	589.5	18.3	3.1
	1986	670.5	28.2	2.7	658.1	17.9	2.7
	1987	767.8	19.2"	2.5"	663.1	5.0"	0.8"
	Total	2784.4	72.6	2.6"	2656.7	54.7	2.1[b]
Planning	1988	825.2	22.7	2.8	891.2	24.1	2.7
After	1989	631.9	5.7	0.9	722.0	7.4	1.0
	1990	488.6	12.3	2.5	442.5	10.3	2.3
	1991	455.6	22.8	5.0	498.8	14.5	2.9
	1992	615.0	43.5	7.2	578.1	12.7	2.2
	1993	741.9	119.9	16.2	799.0	43.0	[illegible]
	Total	2933.0	205.2	7.0"	3040.4	87.9	2.9[b]

Watershed management started in 1988.
[a] Missing data.
[b] Mean value.

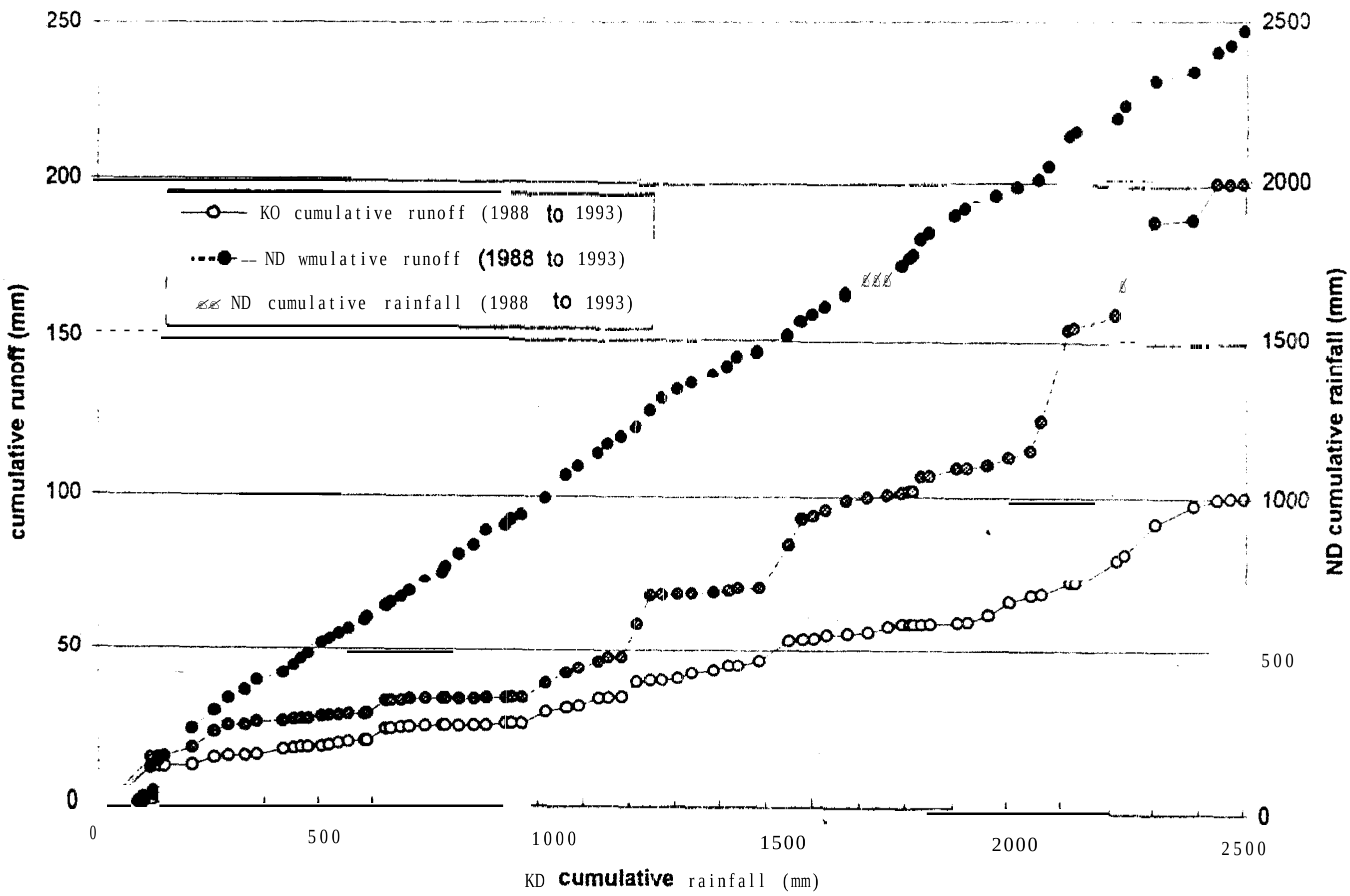

Fig. 4. Cumulative runoff amounts recorded from 1988 to 1993 at the exutories of the control (ND) and developed (KD) basins. The ND basin cumulative rainfall amounts are comparable with the KD basin.

rainfall series. For this representation of the cumulative runoff values, from 1988 to 1993, we extracted from the data set the events generating no flood in both watershed, the missing or uncertain records and. the errents for which rainfall amounts differed more then 40% between the two watersheds. One Can notice the increase, from 1988, of the variation between the two basins.

in the years with high runoff, the conservation meascres had a marked effect on the water balance and the solid transports. For example, in 1991, levels of solid transports were the same in both basins (about 650 kg/ha), but in 1992, they represented 488 kg/ha for the Keur Dianko watershed and more than 1 t/ha for the Ndierguene watershed.

Tht: impact of the watershed management is clearly demonstrated by an event that occurred on 4-5 August 1993 (Fig. 5). Three consecutive rainstorms totaled 179 mm in 24 hours. The floods after the first shower were the same for the two basins, wiith a runoff coefficient of 9% for the developed basin (KD) and 11% for the control one (ND). Floodings caused by the next two showers (very low infiltration conditions) were markedly higher and intense in the Ndierguene watershed (KD: 10% and 14%; ND: 50% and 42%). The solid transports were 1.5 t/ha for the developed basin (KD) and 3.5 t/ha for the control basin (ND).

3.2. Field monitoring

The results of the cadastral survey show a common trend. in both watersheds, to increase cropping areas. In 1990, cropping area represented 55% in the developed basin (KD) and 62% in the control one (ND) (Fig. 2). In Keur Dianko, even after 1988. from 6 to 9 ncw farm plots were slashed from rangeland every year. During the same rime, 5 fields, seriously damaged by erosion, are abandonned in the control basin (ND) and no one in the developed basin (KD).

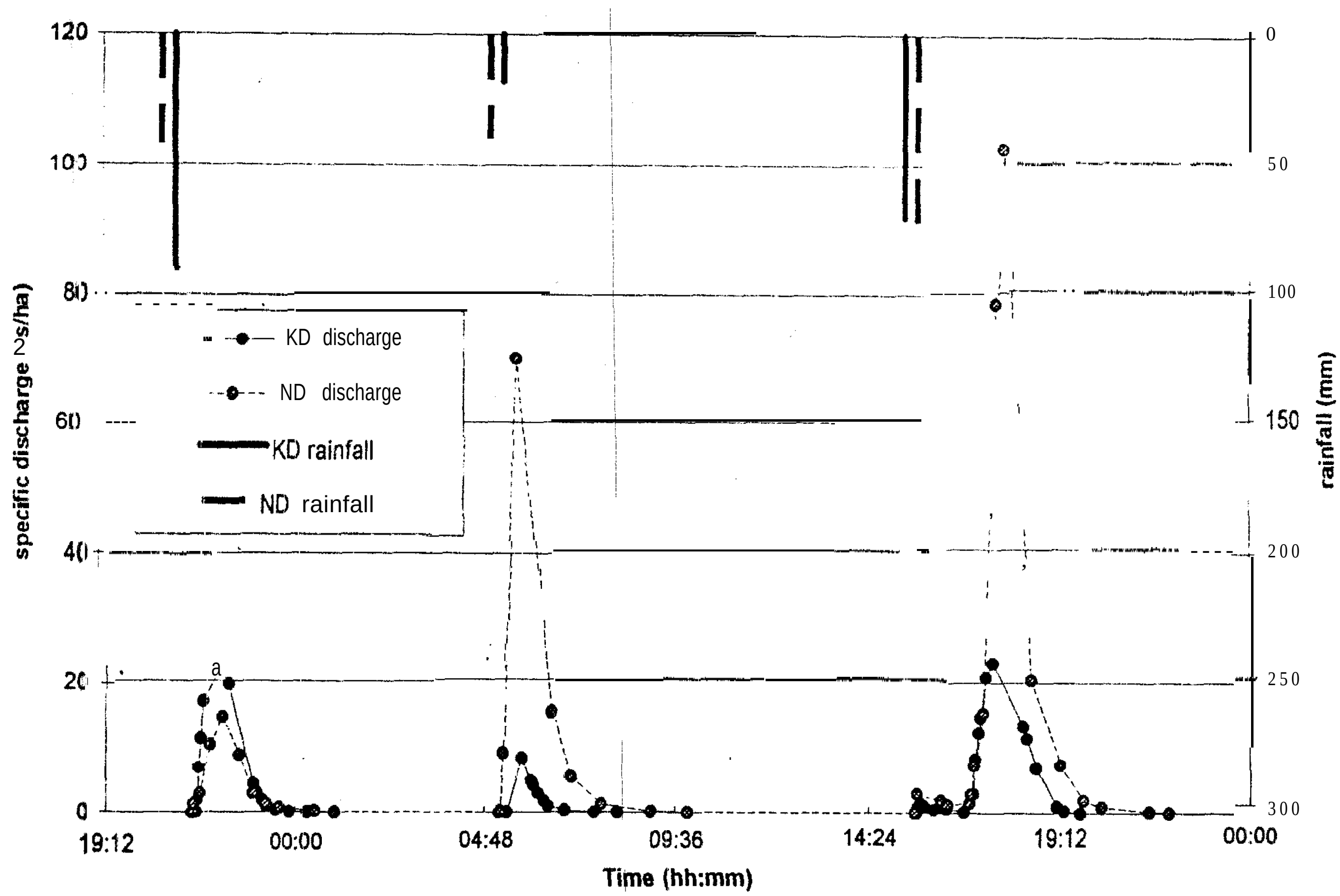

Fig. 5. Rainfall amounts (mm) and specific discharge (l/s/ha) during the 4th and 5th of August 1993. Comparison between the control (ND) and the developed (KD) basins.

Though some trials were condocted, every year, with farmers of Keur Dianko, the proposed cropping practices were diversly adopted. Contour cultivation increased from 20% to 80% of the fields, between 1987 and 1993, thanks to the establishment of the live-hedges. But dry season decompacting, shallow ridging for groundnut crop or shallow earthing up for millet crop increased only from 0% to 20% during the same time. Localized manure application reached only 16% of the plots. Technical and socio-economic reasons of such a failure are analysed in a previous paper (Perez et al., 1996).

Due to this weakness of spreading, but also to variable rainfall conditions, grain yields showed no trend during the whole period (Table 2). Considering annual mean yield or its coefficient of variation, it is obvious that production remained at a very low potential (inter-annual mean yield was 687 kg/ha for both crops) and that heterogeneity between the farm plots was high. The surprising results achieved in 1988, drspite favorable rainfall amounts, were due to intense leaching and flowers aborting.

3.3. Live-hedge monitoring

The growth of the seedlings of shrub species was strongly linked with climatic conditions. In 1988, the exceptional precipitation permitted achieving an average survival rate of 9 1% (from 4700 plants:), but in 1989 and moreover in 1990, for the last setting up of hedges, the survival rates dropped to 74% (from 2100 plants) and 36% (from 410 plants), respectively (Table 3). It must be emphasized that neirher irrigation nor protection were given to the young shrubs. The planting conditions were then crucial for the future of the live-hedge. Once established the death rate of the plants was much lower. Table 3 shows that the growth rate depended also on the planting {conditions. Results given for 1991 must be read with care because pruning activities began during the previous year.

In fact, these global results hide differences between species (Table 4). For example, *Gliricidia sepium* gave bad results from the first year (survival rate: 33%) and *Prosopis juliflora* remained steady only one more year (survival rate: 43%). On the other hand, *Acacia nilotica* and *Bauhinia rufescens* confirmed, in local conditions, their strength and their adaptability, described by other authors (Lal and Stewart, 1990: Vlaar, 1992). Farmers were ver-y sensitive to the survival rate of the plants. considered as a rate of profitability of their work. But they

Table 3
Average survival rates and average growing rates of the seedlings

Date of planting	Date of monitoring					
	Rainfall	Nb	1988	1989	1990	1991
1988	894.2	4700	-	91	85	84
			3 4 $ 1 0	79 ± 35	137 ± 58	145 ± 66
1989	722.0	2100	-		'74	70
				31 ± 11	61 ± 28	63 ± 43
1990	442.5	410	-	-	-	36
			-		31 ± 10	35 ± 12

Results are given for each date of planting and each date of nionitoring.
First line: average survival rate from the planting (%); second line: average cumulative height from the planting (cm).
(Rainfall): annual rainfall (mm); (Nb): number of plants.
All the species are merged.

Table 2
Groundnut (*Arachis hypogea*) and millet (*Pennisetum tiphoïdes*) annual grain yields

Year	Rainfall (mm)	Groundnut grain yield			Millet grain yield		
		Nb	Mean (kg/ha)	CV (%)	Nb	Mean (kg/ha)	CV (%)
1987	663.1	15	1069	45.3	10	821	43.0
1988	894.2	18	629	39.0	7	412	65.0
1989	722.0	19	929	30.6	11	682	44.6
1990	442.5	28	483	43.7	17	448	53.5
1991	498.8	26	569	43.3	21	527	46.2
1992	578.1	24	536	52.6	II	757	27.1
1993	799.0	20	595	34.3	17	1163	33.6

(Rainfall): annual rainfall; (Nb): number of plots; (Mean): average value; (CV): coefficient of variation.
Fields monitoring of the KD basin.

Table 4
Average survival rate from the planting (1988)

Species	Nb	Date of monitoring		
		1989	1990	1991
Acacia nilotica	804	98	96	96
Bauhinia rufescens	1557	96	95	95
Dichrostachys glomerata	118	76	65	63
Gliricidia sepium	60	33	20	18
Acacia mellifera	148	92	a7	85
Parkinsonia aculeata	48	98	83	83
Piliostigma reticulatum	641	84	83	77
Prosopis juliflora	306	83	43	35
Acacia senegal	76	87	83	82
Acacia seyal	177	97	93	93
Ziziphus mauritania	365	79	78	77
Total	4300	91	85	84

These are the main species planted in 1988.
(Nb): number of plants.

noticed that it was useless to get two meters high thorny shrubs to control runoff and erosion! For this reason, a programme of pruning was started since 1990.

Another aspect of the shrubs management was the annual replacing of the ones that died into the existing hedges. From 1989 to 1991. the average rate of substitution wus nearly 18%. For most of the species, the survival rates in this case were equivalent to those recorded in the case of a first planting For example, during the year 1989, 431 plants of *Acacia nilotica* were newly planted, with a survival rate of 82%, while 154 plants were planted as substitutes with a survival rate of 84% (Rautureau et al., 1991).

4. Discussion

Since we expected hydrological effects of the project, the first results were quite disappointing. It took four, years to become obvious that we had to analyse them in terms of conservation rather than restoration. The soil and water conservation practjces only permitted the siowing down of some mechanisms involved in the watershed degradation process. For that reason, there is no rendency to decrease the global runoff rate of the developed basin (KD). But the increasing difference recorded in comparison with the control basin (ND) showed that the natural trend had been modified. In this case, the paired watershed technique was the only experimental method that could pive evidence of this result.

Even in recent reviews on the subject (Amir. 1996; Unger, 19%) there are very few results of studies realised at this scale (1 km^2) comparing developed and control bnsins. At inferior scales (1 ha, 100 m^2), many studies gave evidence of positive results — in terms of restoration -- of developments applied in comparable climatic and human conditions (Vlaar, 1992; Roose, 199-l).

The farmers took a polite interest in hydrological results but they were more responsive to the main gully and adjacent tracks stabilisation. The relation between rills, track and gullies became so evident that every one tried to control the waterways in his field with the help of stone pavments or wood trunks. On the other hand. despite the predictable consequences, farmers continued to slash the upper parts of the hillside. Between the land degradation and the social pressure on tenure, they chose the lesser of two evils. This can partly explain the limited effect of the conservation measures In the Keur Dianko watershed.

After eleven years of monitoring, it seems incredible that we began the planning during the most rainy year of the decade. By a mere chance, the major part of the plantings profited by favourable conditions. What would have been the situation. if we had started two years later? The average survival rate would have dropped to 40% and the farmer's enthusiasm would have disappeared. Today, live-hedges have two main objects for the farmers: to control runoff (and run-on) during the rainy season and to supply fodder during the dry season. For both objects, they get into the habit of creating swaths, at the base of the hedges, with crop and weed residues.

All the labour time requirements were recorded (Ruelle et al., 1990). For the entire project planting hedges required 160 men X day, excluding the nursery activities. Stone line and pavment building required 50 men X day. This theoretically represents 350000 FCFA (1700 FCFA/day in 1988), adding to, approximately, 50000 FCFA for little equipments. The nursery yard required 10 men × day for preparation (fencing, digging) and 70 men × day for seeding, that is to say an amount of 140000 FCFA. So, the cost of this collective work, done between

1988 and 1990, is 540000 FCFA. in fact, this is a theoretical amount because we didn't pay for any salary; but, on the other hand, we didn't include the cost of the support from the scientific staff.

At the hillside scale, the collective benefit cannot be derived from an increasing crop production, as we have seen it. The positive results mentioned above are the tracks and the fields stabilization. By comparison with the control basin (ND), we can take as an hypothesis that four farm plots were saved from irreversible damage. The average field area is **0.5** ha (KD basin: 67 plots on 33 ha) and the average grain yield is 700 kg/ha (i.e pod yield is 1000 kg/ha). Using the unit price of groundnut pods (1988: 90 FCFA/kg), we can estimate the benefit as 180000 FCFA/year. The theoretical cost/benefit balance became steady after 3 years. These results are close to those given by Vlaar (1992) or Rochette (II 989).

Beyond this over-simple demonstration, it is a fact that some of the 20 farmers involved in the watershed management felt somehow swindled. Even though they agreed that there were actual effects, they said they were not totaly paid back for their contribution to the collective effort. This reaction is, partly, due to the relative failure of our cropping practices proposals. Facing the good results of the trials (Perez et al., 1996), it is clear that the major error has been to neglect the linkage between individual and collective actions, the farm plot and the hillside scales.

5. Conclusion

Various techniques aimed at controlling runoff and stabilizing water erosion phenomena were applied in a degraded part of the groundnut cropping basin of Senegal. The conservation measures were set up in different landscape units, with their ecological features and human uses taken into account. Using the paired watershed technique, it has been demonstrated that this land management strategy had actual hydrological effects. After five years, the only agronomic effect was due to the land stabilization. The synergy between runoff control and fertility restoration should have been emphasized to ensure farmer participation and benefits sharing (Roose, 1994). But results are not insignificant: an increasing number of individual farmers and village communities from the neighborhood are now asking for technical assistance so as to apply conservation measures on their land.

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