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Native Forest (Caatinga) Watershed Management for Runoff Inducement for Irrigation

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ABSTRACT

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The results of hydrological investigations for two years on eight levels of native forest (Caatinga) watershed management, principally for runoff inducement for water harvesting for irrigation, are reported. The first four watershed treatments consisted of one or a combination of intensified surface drainage treatments within native forest watershed, clearing alternate contour strips of native forest at 25-cm vertical intervals while alternate strips are maintained in native cover, constructing narrow-based channel terraces below cleared strips and application of common salt in cleared strips for impermeabilization of the soil. The next three watershed treatments are without native forest and the eighth (the last) watershed is maintained undisturbed under native forest cover as a control treatment.

In the arid zones of the Northeast of Brazil, the combination of (i) clearing alternate strips of Caatinga with alternate virgin strips about 30 m wide at 25-cm vertical interval on gently sloped watersheds and (ii) the construction of narrow based channel terraces, can make available for irrigation about 5-11% of the incident rainfall. At the same time this combination helps conserve soil and natural forest ecosystems.

INTRODUCTION

Agriculture in the Northeast of Brazil suffers from climatic variability and a poor soil resource base. The smaller farmers, holding 10 ha or less which constitute 58% of land holdings but only 5% of the total land area, have been reported to be most vulnerable to drought (Hall, 1978). The effects of these factors are acute in the very arid and arid zones of the Northeast of Brazil

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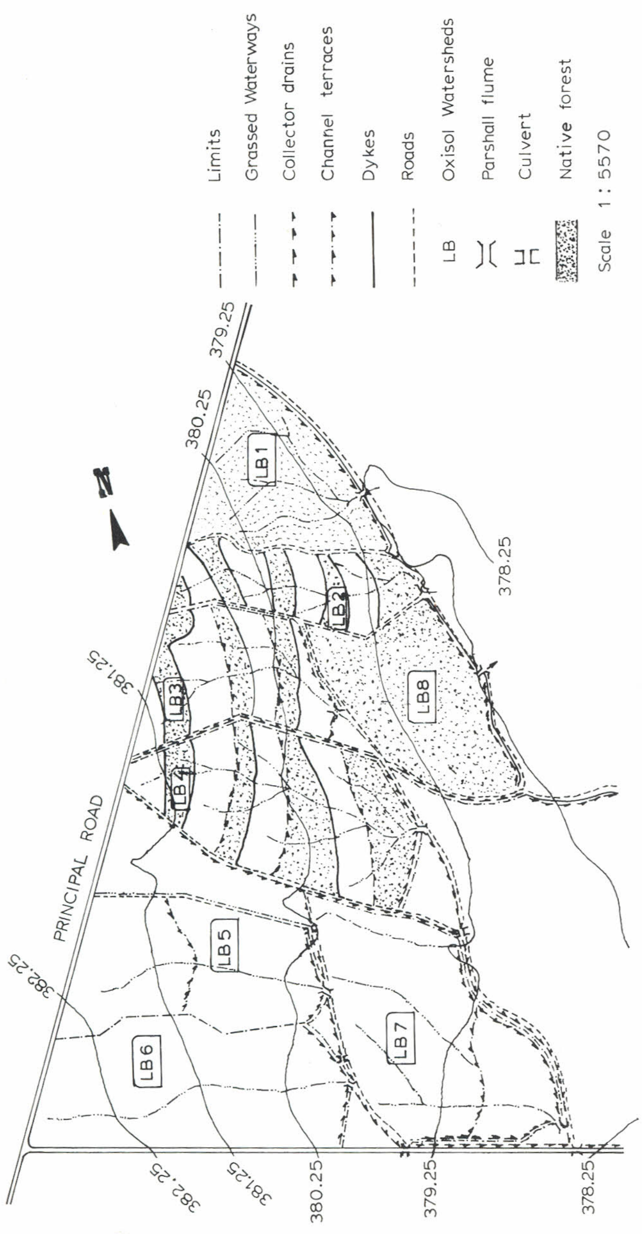

Fig. 1. Oxisol watersheds with different native forest and land management treatments.

which consist of 452 200 and 404 600 km^2 area respectively, out of a total area of about 1.65 million km^2. Most of these areas are occupied by native forests called Caatinga. Small farmers move away from their agricultural lands as soon as there are signs of a drought, often in vain because opportunities to earn a living in cities are rather limited. However, they return to their lands as soon as it rains, in the hope of taking some meagre crops, but often this also proves to be in vain as these rains rarely suffice. Runoff inducement for water harvesting for irrigation is a means to reduce these imbalances in very arid and arid zones, if done in collaboration with nature.

Nowadays new lands are being opened for agriculture, often indiscriminately and, in the process, areas of natural forest (Caatinga) are completely destroyed. Rural populations are deprived of their meagre traditional means of livelihood from native forest and become completely dependent on the vagaries of rainfall.

A detailed review of various runoff inducement methods was recently presented by Sharma et al. (1984). Based on this review, vegetation and cheap land surface management treatments were selected for the present study in arid conditions of Northeast Brazil. Sharma et al. (1984) also discussed the applicability of the runoff-inducement concept to agriculture in arid zones of Northeast Brazil and reported on their recent research efforts on shallow and medium deep oxisols. Some of the results of this research, in particular the effects of alternate strips of native forest (Caatinga) on evaporation reduction in adjacent leeward cleared strips in micro-watersheds have been presented elsewhere (Sharma, 1985; Sharma and Silva, 1986). The objective of the present paper is to present the results of a 2-year hydrologic evaluation of various forest (Caatinga) and land-surface management treatments on the runoff inducement for irrigation and soil conservation on a micro-watershed basis.

METHODS

Eight micro-watersheds were developed at CPATSA-EMBRAPA, Petrolina (PE) in 1982–83 for hydrological evaluation of alternate low cost methods of runoff inducement at a location with either shallow or medium-depth oxisols. They varied in size between 1 ha and 2.7 ha, and together occupied 15.2 ha of virgin native forest (Fig. 1). These eight micro-watersheds were subjected to different degrees of disturbance; one, the control, with undisturbed natural vegetation (LB 8), four with some disturbance to the natural vegetation (LB 1–4) and three in which the natural vegetation was totally destroyed (LB 5–7, see Table 1).

The development work consisted of topographic survey of the land before land clearing to help delineate the hydrologically independent watershed units. For close surveillance and easy approach to the sites, roads were laid on the boundaries of the watersheds. These roads drain separately and do not interfere with the water balance of the watershed units. Collector drains were devel-

TABLE 1

Description of treatments and characteristics of the micro-watersheds at the experimental location in Northeast Brazil

Site	Treatment	Total area (ha)	Area under native forest (% of total)	Density of manually shaped drains (m/ha)	Average slope (%)
LB 1	Intensified drainage	1.5	100	263.5	1.4
LB 2	Strip clearing + intensified drainage	1.1	49	310.4	1.2
LB 3	Strip clearing + intensified drainage + narrow based channel terraces (50 cm vertical interval)	1.4	44	234.0	0.8
LB 4	Strip clearing + intensified drainage + narrow based channel terraces + salt application	2.4	50*	270.5	0.8
LB 5	Completely denuded + narrow based channel terraces (vertical interval 100 cm)	2.1	NIL	91.0	0.9
LB 6	Completely denuded + grass cover	2.4	NIL	104.0	1.2
LB 7	Completely denuded + intensified drainage + narrow based channel terraces + grass cover	2.7	NIL	224.3	0.7
LB 8	Virgin forest, control	1.6	100	NIL**	1.2

*53.8% during 1983–84.
**Shaping of natural drainage was not done to avoid any disturbance to vegetation.

oped to remove the water of LB 5 and LB 6 watersheds so that it did not interfere with the hydrological balance of the LB 7 watershed. Parshall flumes were installed to monitor the runoff efficiency of the different treatments.

The first watershed treatment consists of intensified drainage without disturbing Caatinga native vegetation (LB 1). This was achieved by opening the vegetation for making parabolic-shaped waterways manually on the topographic depressions. The main drain consists of a 1.5 m wide × 15 cm deep waterway while the lateral waterways are only 1 m wide × 15 cm deep. On the second watershed unit (LB 2), alternate strips of land at alternate 25-cm vertical intervals (i.e. 50 cm between the cleared strips themselves), were cleared to comprise about 50% of the area of the watershed. Waterways were developed as on LB 1. On the third watershed (LB 3) narrow-based channel terraces having a maximum of 1 m^2 cross-sectional area of dyke were constructed on the lower side of the cleared strips at 0.3% slope. In the fourth watershed (LB 4) common salt was applied at a rate of 300 g/m^2. Thus this treatment (LB 4) consists of intensified drainage as in the first treatment (LB 1), salt-treated cleared strips and narrow-based channel terraces. It should be noted that these first four treatments are basically different ways of managing Caatinga native vegetation such that the natural plant cover is preserved. The cleared strips are provided with channel terraces below them. The intensified drainage system is aimed at relieving the depression storage of a catchment. Thus these four watershed treatments represent incremental levels of techniques of runoff inducement, namely intensified drainage, strip clearing, channel terraces and salt application.

The next three watershed treatments (LB 5–7) are treatments completely removing Caatinga native vegetation. The first of these three treatments has been superimposed with a main waterway and channel terraces at a vertical interval of 100 cm for soil conservation on completely bare soil (LB 5). In the next watershed treatment, buffel grass was planted to protect the soil and make the system productive and a main waterway was shaped on the main topographic depression (LB 6). The last of these treatments consists of narrow based channel terraces, intensified waterways for relieving depression storage, and buffel grass (LB 7). Thus these three treatments present different levels of drainage, channel terraces and grass for soil protection after the complete removal of Caatinga native vegetation.

The eighth and last watershed unit is a control. The natural vegetation is maintained without any disturbance. This watershed has natural drainage similar to the others except that the topographic depressions have not been shaped to avoid any disturbance to vegetation. For this reason Fig. 1 does not show any drainage lines in the LB 8 watershed and the manually shaped drainage density of this watershed is shown in Table 1 to be nil.

These watersheds are located within 500 m of a meteorological station. Hence, the rainfall data of this meterological station was taken to represent the rainfall in the watersheds also. However, in the first year (1983–84) variation among watersheds was noted. So in the second year (1984–85) rain gauges were installed in each of the watershed units as additional checks although the meteorogical station data were used to calculate rainfall intensity.

The daily runoff efficiency was calculated by dividing the runoff of the day of the event by the rainfall of the day. Annual runoff efficiency was obtained by summing up the daily runoff data calculated from stage recorder charts of the installed Parshall flumes and then dividing the annual runoff by total annual rainfall. For calculating annual soil loss, water samples were collected from the runoff water in the Parshall flume every time runoff took place. However, during 1983–84 this was not possible, and hence water samples were drawn from the left-over water in the flumes after a runoff event. While this is not an

TABLE 2

Annual runoff efficiency and soil loss from various micro-watershed treatments of native forest management for the experimental location in Northeast Brazil

Site	Annual[1] Runoff Efficiency[2] (%)		Annual soil loss (kg/ha)	
	1983-84	1984-85	1983-84[3]	1984-85
LB1	1.2 (1.08)	0.08	59.90	0.42
LB2	(3.72)[4]	1.05	45.21	9.03
LB3	10.77(10.00)[5]	5.46	135.32	42.93
LB4	11.62(11.67)	7.67	191.40	102.11
LB5	28.07(29.67)	24.52	141.33	233.2
LB6	N A[6]	10.27	N A	107.44
LB7	N A	8.38	N A	105.25
LB8	0.00028(0.0003)	0.0	1.0	0.0

[1]For 1983-84, from 28 November 1983 to 30 May, 1984, total rainfall was 601 mm. For 1984-85, from 15 November, 1984 to 30 May, 1985, total rainfall was 775 mm.
[2]Annual runoff efficiency is defined as the percentage of runoff produced by the rainfall on an annual basis.
[3]Estimate based on water samples from left-over runoff in Parshall flumes at the end of a runoff event.
[4]The first 3 runoff events could not be recorded.
[5]The data in brackets is when the first 3 runoff events are removed. Thus the figures in brackets can be directly compared.
[6]N A=Not Available.

accurate way to measure soil loss, the 1983–84 data can still be used for comparison of various treatments within the same year.

RESULTS AND DISCUSSION

The rainfall data for the day of the runoff event, daily rainfall intensity, the runoff produced, calculated daily runoff efficiency and daily soil loss for both the years 1983–84, and 1984–85 have been reported elsewhere (Sharma, 1985). In the interest of brevity this voluminous data, though costly and rare to find in Northeast Brazil, is not reproduced here. In Table 2 these data have been summarized to give annual runoff efficiencies and annual soil losses for various treatments on the various micro-watershed units (LB 1–8). Tables 3 and 4 show the effects – of number (W) and intensities of rainfall events when runoff occurred in at least one of the treatments (the rest of the rains were very small in quantity), and eight methods of managing native forest (LB 1–8) – on the number of runoff occurrences (X_1), mean amount of runoff (X_2) and the mean amount of eroded soil (X_3).

In calculating annual runoff efficiency, the annual rainfall also includes all

TABLE 3

Relationship between number and intensities of rainfall events, eight methods of managing native forest and the amounts of runoff and eroded soil from the experimental location in the Northeast Brazil during 1983–84

Rainfall		Description of variants	Watershed treatments							
Intensity (mm/h)	Number of events (*W*)		Management of natural vegetation				Complete elimination of natural vegetation			Un-treated control
			LB1	LB2*	LB3	LB4	LB5	LB6	LB7	LB8
1–19	9	Number of occasions with runoff, X_1	1	5	7	9	7	N A	N A	Nil
		Mean amount of runoff when runoff occurred (mm), X_2	0.13	0.26	0.78	0.99	2.02	N A	N A	Nil
		Mean amount of eroded soil (kg/ha), X_3	0.74	0.56	1.08	2.16	1.17	N A	N A	Nil
20–39	4	X_1	3	2	3	4	4	N A	N A	Nil
		X_2	1.32	4.01	9.48	7.07	18.66	N A	N A	Nil
		X_3	8.68	3.27	9.05	5.69	11.14	N A	N A	Nil
40–59	4	X_1	4	4	4	4	4	N A	N A	1
		X_2	0.66	3.2	4.77	6.33	18.78	N A	N A	0.15
		X_3	3.89	8.87	9.01	27.19	13.26	N A	N A	0.85
≥60	2	X_1	1	1	2	2	2	N A	N A	1
		X_2	1.48	0.29	5.88	3.63	7.31	N A	N A	0.02
		X_3	16.61	0.39	32.28	11.47	17.77	N A	N A	0.13

*The records of first three events are not available.
N A = Not available.

those rainfall events which did not produce any runoff. In both the years of the study (1983–85), rainfall was well above the 400-mm norm; however, this provides an opportunity to evaluate the different variants.

In general the runoff efficiency for all the watershed treatments was higher during 1983–84 than during 1984–85 even though there was 775 mm rain during 1984–85 while 1983–84 had only 601 mm rainfall (Table 2). This is so because during 1983–84 (Table 3) the rainfall intensities were much higher than in 1984–85 (Table 4). For example, six rainfall events of intensities greater than 40 mm/h were observed out of a total of 19 in the first year while during the second year there were only two rainfall events out of a total of 24 that exceeded 40 mm/h intensity. Hence, a comparison of mean runoff values (X_2) in Tables 3 and 4 clearly demonstrates that though the first year had considerably less total rainfall, it produced more runoff than the second year in all watersheds.

TABLE 4

Relationship between numbers and intensities of rainfall events, eight methods of managing native forest, and the amounts of runoff and eroded soil from the experimental location in the Northeast Brazil during 1984-85

Rainfall		Description of variants	Watershed treatments							
Intensity (mm/h)	Number of events (*W*)		Management of natural vegetation				Complete elimination of natural vegetation			Untreated control
			LB1	LB2	LB3	LB4	LB5	LB6	LB7	LB8
1-19	7	Number of occasions with runoff, X_1	Nil	1	3	6	7	2	2	Nil
		Mean amount of runoff when runoff occurred (mm), X_2	Nil	0.29	1.67	2.18	34.54	4.24	3.98	Nil
		Mean amount of eroded soil (kg/ha), X_3	Nil	0.97	1.44	2.05	2.90	3.1	3.93	Nil
20-39	15	X_1	2	4	10	14	15	6	5	Nil
		X_2	0.27	1.47	3.03	2.82	7.92	7.54	8.08	Nil
		X_3	0.19	1.74	2.8	4.7	9.95	12.67	11.83	Nil
40-59	1	X_1	1	1	1	1	1	1	1	Nil
		X_2	0.09	2.15	7.49	7.05	25.01	18.09	17.14	Nil
		X_3	0.04	1.89	10.26	19.64	41.51	25.14	37.19	Nil
$\geqslant$60	1	X_1	Nil	1	1	1	1	1	1	Nil
		X_2	Nil	0.27	2.14	3.99	19.71	2.16	1.63	Nil
		X_3	Nil	0.03	0.26	2.88	31.14	0.09	1.03	Nil

From the annual data of soil loss in Table 2 and the mean amount of eroded soil data (X_3) in Tables 3 and 4, it can immediately be concluded that soil losses due to erosion for all eight treatments were of very low order and are well within the safe permissible limits of erosion. This is so because the slopes of the eight watersheds (Table 1) are gentle.

Effect of intensified drainage within Caatinga (comparison of LB 1 and LB 8)

The surface drainage density of manually shaped waterways in watershed LB 1 is 263.5 m/ha as compared to no manually shaped drainage in watershed LB 8 (control), although the natural drainage pattern of LB 8 is similar to other watersheds (Table 1). Except for this both these watersheds are covered completely by native forest. The annual runoff efficiency of the LB 1 watershed was 1.2% and 0.08% during 1983–84, and 1984–85, respectively. The difference in the efficiencies of the 2 years can be attributed to the appreciably greater number of rainfall events (six) of higher intensities (⩾40 mm/hr) in the 1st year as compared to only a few (two) rainfall events of similar intensities in the 2nd year (see Table 3 and 4). The watershed LB 8 had annual runoff efficiency of zero order and almost negligible runoff during both years. Thus the effect of intensifying surface drainage within the native Caatinga can be of the order of up to about 1.2%. Virgin native Caatinga forest allows virtually no runoff on gentle slopes. This fact is easily observable but often not believed.

Effect of clearing alternate contour strips of Caatinga (comparison of LB 2 with LB 1 and LB 8)

The watershed LB 2 had 51% of its total area cleared of Caatinga in alternate strips at alternate 25-cm vertical intervals. The windbreak effects of Caatinga strips on adjacent leeward cleared strips are very significant and it has been clearly demonstrated by the authors elsewhere that about 6–37% reduction in evaporation rate takes place on the leeward cleared strips (Sharma and Da Silva, 1986). This effect is positive up to 30-m wide cleared strip in this region.

Watershed LB 2 has a drainage density of 310.4 m/ha and a slope of 1.2%. In the 1st year (Table 2), excluding the first three runoff events which could not be recorded due to delay in arrival of stage recorder for this watershed and during which period 98.1 mm of rain fell, the annual runoff efficiency was 3.72%. If the first three events for watershed LB 1 are not considered an annual runoff efficiency of 1.08% is seen. Thus in the 1st year the clearing of alternate strips of Caatinga contributed 2.64% to the annual efficiency. In the 2nd year this contribution was of the order of about 1%. Clearing of about 51% of the area of watershed LB 2 and providing surface drainage gives an annual runoff efficiency of the order of 1–4% as compared to the control. Runoff occurred on five and three occasions in higher mean amounts on treatment with alternate cleared strips (LB 2) in comparison to a single event on LB 1, even when the rainfall intensity was less than 20 mm/hr, in the 1st and 2nd years, respectively (see Tables 3 and 4).

Effect of narrow-based channel terraces (comparison of LB 3 with LB 2)

Watershed LB 3 having 56% cleared area in strips, a drainage density of 234 m/ha, and a slope of only 0.8%, has narrow-based channel terraces at 0.3% slope with a maximum of 1 m^2 cross section below each cleared strip. The two annual runoff efficiencies of this watershed were 10.77% and 5.46%, respectively. Thus this watershed treatment (LB 3) which has a slope of only 0.8% as compared to 1.2% of the control watershed LB 8, has an annual runoff efficiency of the order of 5–11%. When this watershed is compared with the watershed LB 2, the effect of the narrow-based channel terraces is to increase the annual runoff efficiency by about 6.3% (excluding first three events) and

4.4% in the 2 years respectively. This is so because when narrow-based channel terraces are not provided below each cleared strip, the runoff enters the native forest strips which, having very high infiltration rates, rapidly absorb the runoff. This can be the only reason that at rainfall intensities below 40 mm/h runoff occurred on more occasions and in much greater amounts in LB 3 than LB 2 in both years (Tables 2 and 3). The channel terraces do not allow the runoff from cleared strips to enter Caatinga vegetation strips and lead the runoff out through the surface drains, transmission losses through the drains being much less than losses in the Caatinga strips.

This is an important finding of this research project and has very wide implications for water harvesting for irrigation. By simply adding narrow-based channel terraces below cleared strips runoff efficiency is increased manyfold. Thus, rather than to indiscriminately destroy native forest so as to increase the amount of water available for distribution in Northeast Brazil, use of the type of treatment in watershed LB 3 permits sufficient water supplies even at gentle slopes while conserving the Caatinga ecosystem and without creating any significant erosion problems. Conversely, for regions where additional runoff is not needed but additional land is required for rainfed agriculture, land should be only cleared of Caatinga vegetation in alternate contour strips. In such instances, terraces need not be created. In such a management system, higher water-use efficiencies can be achieved for the crops grown in these strips by the windbreak effects of Caatinga strips on evaporation reduction (Sharma and Da Silva, 1986).

Effect of salt application on alternate strips cleared of Caatinga (comparison of LB 4 with LB 3)

The micro-watershed LB 4 is similar to the LB 3 except that 300 gm/m^2 of common salt was incorporated on the cleared strips for decreasing the soil permeability. The quantity of salt was calculated based on the cation exchange capacity of the soil. When LB 3 and LB 4 are compared (Table 2) the contribution of salt to annual runoff efficiency is of the order of 0.85% and 2.25% for the 2 years. Though the contribution is significant it is doubtful if it will compensate for the cost of salt and its application. In addition, reapplication after every 3 or 4 years may be needed. The contribution of salt in the 1st year is of a relatively lower order since it takes some time for the salt to leach down the profile of the soil and react. For rainfall intensities greater than 20 mm/h, although the number of occasions with runoff is consistently higher or equal in LB 4 as compared to LB 3 in both the years, the mean amount of runoff is not consistently so. This can mean that for as yet undetermined reasons salt treatment may not lead to an increase in the amount of runoff for a given storm beyond 20 mm/h intensity.

Effect of complete destruction of the native forest (LB 5)

The micro-watershed LB 5 was completely denuded of Caatinga forest cover. Two narrow-based channel terraces were constructed at a vertical interval of about 1 m each. This watershed had maximum runoff occurrence and maximum amount of runoff (Tables 3 and 4). The annual runoff efficiencies were 28.07% and 24.52% for the 2 years (Table 2). Thus, complete destruction of Caatinga results in the highest runoff; in addition to many other adverse effects to the Caatinga ecosystem, this will certainly create the problem of flash floods, while this great a quantity of water in any case may not be needed.

Effects of grassing a completely denuded watershed (comparison of LB 6 and LB 7 with LB 5)

Watersheds LB 6 and LB 7 (Fig. 1) were planted to buffel grass during the first year after native forest Caatinga was completely removed. In watershed LB 7, a narrow-based channel terrace was also provided at 1-m vertical intervals. Watershed LB 6 has a slope of 1.2% and drainage density of about 104 m/ha (Table 1). Watershed LB 7 has a slope of only 0.7% but a drainage density of 224.3 m/ha. These watersheds could not be monitored for runoff in 1983–84 season. However, the data of 1984–85 in Table 2 does demonstrate that by planting grass the annual runoff efficiency was reduced to 10.27% in watershed LB 6 and 8.38% in watershed LB 7, in comparison with 24.52% for completely denuded watershed LB 5. It is not possible to identify the part played by terracing and watershed slope on differences in the hydrological behavior of these two watersheds as the data available (Table 4) is only for 1 year.

Behavior of completely virgin native forest Caatinga watershed (LB 8)

The micro-watershed LB 8, which has a slope of 1.2%, was monitored for runoff and soil loss without any disturbance of the native forest cover. Even the natural topographic depressions were not smoothed to form a regular waterway, to avoid any disturbance. As is obvious from Tables 2, 3 and 4 there was practically no runoff at all from this watershed except about 0.17 mm during the 1983–84 season. This phenomenon can easily be observed in the region in any watershed of gentle to moderate slopes. In addition, Caatinga is extremely well adapted to the region and it is one of the unique natural vegetations which has evolved over ages as an extremely drought resistant native vegetative cover. It stores large quantities of water in root bulbs and thus can withstand many years of drought. In addition to being extremely efficient at soil and water conservation as demonstrated here, it provides a natural habitat for the wild animals in an extremely arid environment of the Northeast of

Brazil and has many other uses. For these reasons and the water and soil conservation characteristics demonstrated here, it can be stated that if there is any single factor that has saved the Northeast of Brazil from turning into a desert over the ages, it is Caatinga native forest. Hence any agricultural development work should be carried out in harmony with it.

In general the various micro-watershed treatments based on their runoff efficiencies can be ranked as:

$$\text{LB } 5 > \text{LB } 6 \geqslant \text{LB } 7 > \text{LB } 4 > \text{LB } 3 > \text{LB } 2 > \text{LB } 1 > \text{LB } 8$$

The ranking of these treatments from the point of view of erosion is also similar though the level of erosion is well within the safe permissible limits.

CONCLUSIONS

Significant quantities of runoff can be induced for irrigation by applying incremental levels of native forest and land surface management techniques on the virgin native forest watersheds of gentle slopes without creating excessive erosion, at the same time preserving the native forest ecosystem. The best combination for inducing runoff in arid zones of the Northeast of Brazil, as determined by this study, is clearing alternate Caatinga strips on contour while maintaining alternate Caatinga strips in natural form, and by constructing small narrow-based channel terraces on the lower side of cleared strips such that the runoff from cleared strips is not allowed to enter the Caatinga strips. In addition sufficient surface drains should be provided to reduce depression storage of a forest watershed and to take the water out to the water storage facilities.

In those areas where runoff inducement is not needed, native Caatinga forest provides the best form of soil and water conservation. On completely denuded watersheds, planting grass will drastically lower the runoff losses. If additional land is to be cleared for rainfed agriculture, clearing contour strips of Caatinga and leaving alternate contour strips undisturbed (without terraces) reduces crop water requirements in the cleared strips and runoff drastically while maintaining native vegetative ecosystems for natural habitat and other human and animal uses.

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