Hydrological behaviour of first generation coppiced bluegum plantations in the Nilgiri sub-watersheds

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Abstract

The bluegum (*Eucalyptus globulus*) has been widely grown in different parts of the world for multiple purposes. However, the possible adverse effect of converting natural forest watersheds into bluegum plantations on surface and sub-surface hydrology has been a major concern for researchers and planners. This paper critically evaluates the implications of coppiced bluegum plantations on hydrological behaviour during the 10 years of the second rotation using the paired watershed technique in a montane temperate humid climate. The coppiced bluegum growth (1982–91) on 59% of the catchment area reduced the mean annual total runoff by 25.4% and base flow by 27% over the natural grassland as compared with 16% and 15%, respectively, during the first rotation of 10 years. Regression relationships between observed and computed monthly values indicated a relatively higher reduction in the total as well as base flow during the first coppiced growth as compared with the first rotation. Reduction in runoff was at a maximum during July to October, which was ascribed to greater availability of rain water and hence its utilization during this period. The reduction during the dry period (January–April) is crucial for sustaining dry weather flow in the hydro-electric reservoirs. The increased utilization of water during the second rotation was as a result of the deep root system right from the earliest growth which produced 42% more biomass and 40% higher economic returns (at 1982–83 price level) than the first rotation. For the year following the harvest of bluegum trees of the first rotation, the hydrological behaviour was similar to the pre-treatment conditions. The maximum growth of the coppiced shoots height and diameter at breast height (DBH) was noticed during second to fifth year as compared with fourth year onward in the first rotation. Moisture extraction from deeper soil layers by coppice growth was significant ($\alpha = 0.01$) which was not true for the first rotation. Direct contact of tap roots with the ground water table was not observed during the second rotation even through an extensive network of lateral roots was present. © 1998 Elsevier Science B.V. All rights reserved.

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1. Introduction

The planting of *Eucalyptus globulus* has been of great concern to hydrologists, environmentalists, ecologists and local communities as it is suspected to have adverse effect on soil as well as surface and ground water resources. Several studies have been conducted in the past to evaluate the hydrological, growth, and economic aspects of planting eucalyptus species in natural catchments (Bacon et al., 1993; Calder et al., 1993; Stoneman, 1993). In India, Samraj et al. (1988) and Sharda et al. (1988) showed that conversion of natural grasslands into bluegum plantations reduced water yield by 16% during the first

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rotation of 10 years. From the economic point of view, it has been established that 3–4 rotations of *Eucalyptus globulus* are possible, as thereafter the regeneration capacity is lost. However, the information on the hydrological behaviour of coppiced bluegum plantations is relatively scarce though some scattered studies have been reported from other agro-climatic regions (David et al., 1994). Since the findings of such studies are mostly location specific, it is necessary to conduct similar trials and document the recommendations for effective planning and management of bluegum plantations in a given region.

Following on from earlier studies (Samraj et al., 1988), bluegum plantations were harvested in 1982 after the first rotation of 10 years and then allowed to coppice. The focus of the present study is to critically examine the hydrological behaviour of first generation coppiced (second rotation) bluegum together with growth and economic aspects. The results of first and second rotations have also been compared.

2. Materials and methods

Two adjacent watersheds, about 32 ha each, having identical physiographic characteristics were selected in 1964 at the Glenmorgan Research Farm of the Central Soil and Water Conservation Research and Training Institute, Research Centre, Udhagamandalam in the Nilgiri Hills of South India. The study area is located 24 km away from Udhagamandalam on the Udhagamandalam–Mysore State highway at latitude and longitude of 11°28′10″ N and 76°37′14″ E, respectively, in Wenlock Downs forest reserves in the Nilgiris district of Tamil Nadu State (Fig. 1). The region experiences a montane temperate humid climate with an average annual rainfall of 1380 mm, most of which is received from the south-west monsoon and north-east monsoon. The temperatures are mild with a maximum value of 26°C during April and May (Anonymous, 1987). For a detailed description of watershed characteristics and other climatic features, see Samraj et al. (1988). The soils are lateritic and derived from Charnockites with texture
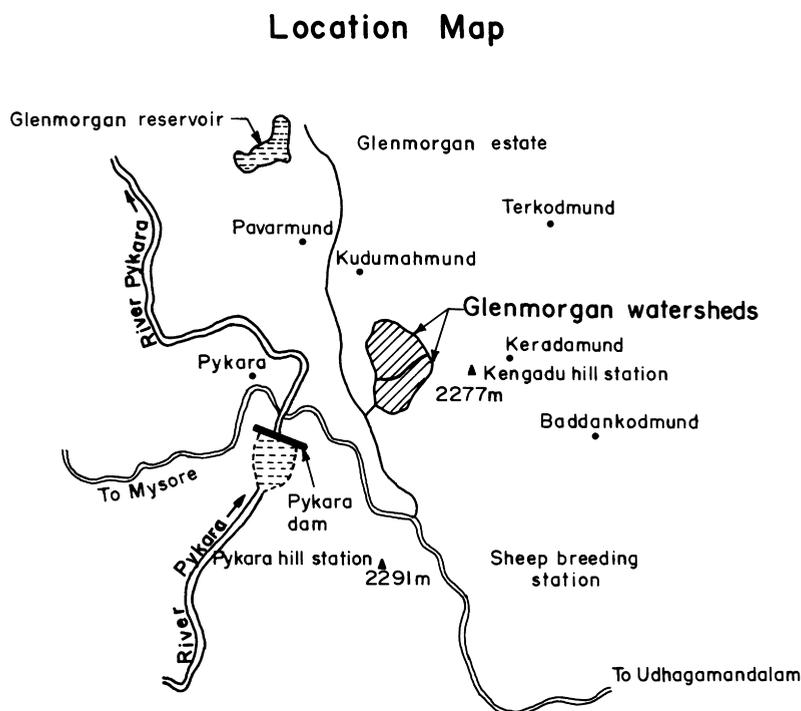
Location Map

Fig. 1. Location map of Glenmorgan watersheds in Western Ghats of India.

varying from sandy loam to sandy clay loam. The field capacity, wilting point and bulk density have been reported as 28.6%, 18% and 1.33 g cm^{-3}, respectively (Anonymous, 1987). For recording runoff, automatic stage level recorders with 2:1 broad crested triangular weir were installed at the outlet of both the watersheds, A and B, during 1968. A small meteorological laboratory was also established near the ridge, demarcating the boundary of the two watersheds to record various climatological parameters like rainfall, temperature, open pan evaporation etc.

After a calibration period of 4 years (1968–71), bluegum (*Eucalyptus globulus*) was planted at a spacing of 2×2 m in one of the watersheds (B) during July, 1972 above the frost line covering an area of 18.76 ha (59%). The rest of the area (41%) in watershed B and the entire watershed A were kept under natural conditions of grasslands (grazed) and savanna vegetation 'Shola'. The silvicultural management practices consisted of felling and coppicing of the trees at 10 years rotation and final felling and replanting after the fourth rotation of 10 years.

The soil moisture measurements were taken at weekly intervals upto 0.5 m and 1 m sampling depths during both the rotations. The fluctuations in ground water levels were recorded in the swamps through pipe wells installed to a depth of 1.25 m and along the slope through piezometric wells installed to a depth of 5 m. The observations on height, growth and tree diameter at breast height (DBH) of bluegum were recorded regularly during the first and second rotation.

Based upon runoff data collected during the calibration period, regression equations were developed for total runoff, surface runoff and base flow in watersheds A and B as follows (Samraj et al., 1988):

$$Y_1 = -4.4377 + 1.1736X_1 \ (r = 0.98) \tag{1}$$

$$Y_2 = 0.0525 + 0.9491X_2 \ (r = 0.98) \tag{2}$$

$$Y_3 = -6.3403 + 1.3032X_3 \ (r = 0.98) \tag{3}$$

Where: Y_1, Y_2 and Y_3 are total runoff, surface runoff and base flow, respectively in watershed B (mm); and X_1, X_2 and, X_3 are total runoff, surface runoff and base flow, respectively, in watershed A (mm). These equations were subsequently used to quantify the effect of bluegum plantations on water yield. The Student's *t*-test (Varshney, 1977) for level of significance and standard correlation methods (Ezekiel

and Fox, 1959) for rainfall–runoff relationships were employed in the statistical analysis. Prediction limits (Snedecor, 1956) at the 95% level were computed for the total runoff during second rotation to determine the significance of changes between the two rotations.

3. Salient findings of the first rotation

After the first rotation (1972–81) of 10 years, the bluegum trees were felled during 1982 at 30 cm height above the ground level, retaining all the shoots of coppice growth. The analysis of runoff data during the first rotation of 10 years revealed that bluegum brought about a significant ($\alpha = 0.01$) reduction of about 16% in the total expected water yield from natural grasslands. On average, the expected total flow and base flow under natural conditions of grassland and 'Shola' were 31% and 22%, respectively, of the expected rainfall of the region. Maximum monthwise reduction both in total flow and base flow as a result of the bluegum plantations occurs during July–November corresponding to the maximum rainfall period.

During the dry season months (January–April), the reduction in base flow was 23% at 50% probability and is very crucial for sustaining dry weather flow in the hydro-electric reservoirs. No adverse effect of bluegum plantations on soil erosion was noticed and the water remained as clear as in the open grasslands. The moisture monitoring at 0.5 m and 1 m sampling depths inferred that the bluegum extracted most of the moisture from the upper soil layers and the deeper soil layers were not tapped. The bluegum interaction with the ground water table was insignificant and the roots remained well above the phreatic surface. The total income of Rs. 3250 ha^{-1} year^{-1} from different components of bluegum trees suggested conversion of natural grassland into bluegum plantations was worthwhile for economic considerations provided it does not adversely affect the water yield into hydro-electric reservoirs.

4. Results and discussion — second rotation

The coppice shoots of bluegum retained after the harvest of first rotation were allowed to grow during the second rotation (1982–91). The regression

equations developed during the calibration period (1968–71) were used to compute the values of total runoff, surface runoff and base flow for the watershed planted with bluegum (B). The harvesting of the second rotation bluegum was undertaken during 1992. In the following sections, the effect of coppiced bluegum on water yield, soil moisture and biomass production during the second rotation are discussed.

4.1. Hydrological data analysis

The computed values of total runoff, base flow and surface runoff obtained by using the regression equations were compared with the observed values of the planted watershed B to analyze the effect of bluegum plantations on water yield reduction during the second rotation.

4.1.1. Annual runoff

Table 1 presents the yearly rainfall, computed and observed values of total runoff and base flow in the planted watershed B during the second rotation. The analysis revealed that the coppiced bluegum significantly ($\alpha = 0.01$) reduced total runoff by 25.4% (937.8 mm) comprising a 10% (184.0 mm) reduction in surface runoff and a 27% (415.3 mm) reduction in base flow. The highest computed runoff (756.7 mm) and the corresponding reduction in water yield (210.9 mm) was observed during the highest rainfall

(1898.2 mm) year of 1991. The occurrence of total runoff in the natural catchment and the reduction in water yield as a result of the bluegum plantations followed the pattern of rainfall distribution. The base flow and its reduction also exhibited a similar trend. The amount of reduction in total runoff or base flow was, however, a function of growth rate of bluegum which varied over the years as discussed latter.

4.1.2. Monthly runoff and low flow analysis

The mean monthly reductions in total runoff, surface runoff and base flow for the second rotation are presented in Table 2. From the pooled monthwise analysis, it was observed that a major part of the mean annual reduction caused by bluegum plantations occurred during the months from July through October. It amounted to 68%, 76% and 56% of the mean annual reduction in total runoff, surface runoff and base flow, respectively, with maximum reduction in October. Since the rainfall during this period was about 60% of the mean annual rainfall, it was inferred that reduction in water yield by bluegum was directly related to the availability of rain water during the south-west and north-east monsoon seasons.

The impact of bluegum on water yield during the dry period (January–April) was also studied during the second rotation. The rainfall during this period was only about 8% of the mean annual rainfall and runoff mostly appeared as base flow. The bluegum

Table 1

Observed and computed values of total runoff, surface runoff and base flow for the planted watershed (B)

Year	Rainfall (mm)	Total runoff (mm)		Surface runoff (mm)		Base flow (mm)	
		Computed	Observed	Computed	Observed	Computed	Observed
1982	1131.0	201.8	201.1	53.4	79.0	142.4	122.1
1983	1206.9	245.2	198.4	81.9	97.6	146.3	100.8
1984	1468.9	420.6	287.3	242.5	197.1	148.5	90.1
1985	1207.8	283.4	231.2	102.2	100.1	174.2	131.1
1986	1349.6	327.3	266.5	123.5	118.8	193.3	147.7
1987	1076.7	292.5	190.8	130.7	94.5	147.1	96.3
1988	979.8	326.0	211.4	149.1	117.5	141.1	93.9
1989	1456.6	562.9	410.0	332.2	284.8	152.1	125.2
1990	1311.3	280.6	216.7	143.1	127.0	99.6	89.8
1991	1898.2	756.7	545.8	447.1	405.3	208.1	140.4
Total	13086.8	3697.0	2759.2	1805.7	1621.7	1552.7	1137.4
Mean annual	1308.7	369.7	275.9	180.6	162.2	155.3	113.7
% reduction		25.4		10.2		26.7	

Table 2
Average monthly reduction in total runoff, surface runoff and base flow due to bluegum plantations in the second rotation (mm)

Month	Rainfall	Observed 'B'			Computed 'B'			Deficit (Computed − Observed)		
		TR	SR	BF	TR	SR	BF	TR	SR	BF
Apr.	71.3	3.8	1.2	2.6	4.9	2.0	2.9	1.1	0.8	0.3
May	111.1	7.0	3.1	3.9	9.0	4.0	5.0	2.0	0.9	1.1
June	166.4	16.3	9.6	6.7	21.8	13.1	8.7	5.5	3.5	2.0
July	233.0	60.9	39.8	21.1	78.6	53.9	24.7	17.7	14.1	3.6
Aug.	221.2	61.3	42.4	18.9	78.4	52.3	26.1	17.1	9.9	7.2
Sep.	133.6	27.3	11.9	15.4	37.7	19.0	18.7	10.4	7.1	3.3
Oct.	165.1	40.4	25.1	15.3	58.6	38.0	20.6	18.2	12.9	5.3
Nov.	70.0	24.1	9.4	14.7	33.8	13.6	20.2	9.7	4.2	5.5
Dec.	64.9	20.5	10.5	10.0	27.9	14.7	13.2	7.4	4.2	3.2
Jan.	9.9	7.4	0.2	7.1	9.6	0.3	9.3	2.2	0.1	2.2
Feb.	5.9	3.9	0.1	3.8	4.6	0.1	4.5	0.7	0.0	0.7
March	17.9	3.2	0.2	3.0	4.0	0.5	3.5	0.8	0.3	0.5

plantation lowered the total runoff significantly ($\alpha = 0.01$) during this period. The 6.9% of the mean annual water yield occurring in the natural grasslands during the dry period (January–April) was further reduced by 28.6% by coppiced bluegum. Hence, this reduction in the dry period, though small (72.7 mm for the second rotation), was very crucial for sustaining dry weather flow in hydro-electric reservoirs downstream. The base flow behaviour also followed a similar trend and was reduced by 24% during the dry period as a result of the bluegum plantations. This agrees with the reported findings of the first rotation (Sharda et al., 1988) though the percent reduction in total runoff as well as base flow during the dry period was of higher magnitude in the second rotation.

4.1.3. Comparison of first and second rotations

The reduction in total water yield due to bluegum plantations during the first and second rotations is presented in Fig. 2. The mean annual reduction was found to be statistically significant in both the rotations amounting to 16% and 25.4%, respectively, of the expected runoff under natural grasslands and 'Shola'. The average annual rainfall of the first rotation (1569 m) was 14% higher than the long-term average annual rainfall (1380 mm) whereas in the second rotation (1309 mm), it was closer to the long-term average being lower by only 5%. However, a higher average annual reduction of 7% of rainfall was observed in the total runoff during the second rotation as compared with 5.6% during the first rotation.

As is evident from Fig. 2, the reduction in total runoff during the first 3 years (1972–74) of the first rotation was negligible. Excluding this period, the reduction in total runoff for the 7 years period (1975–81) was 840.4 mm which is 21.5% of the expected runoff under natural grasslands and 'Shola' as compared with 16% reported earlier for the entire rotation period of 10 years (Samraj et al., 1988). Similarly, the recomputed reduction in base flow for 7 years period of first rotation is 547.9 mm or 20.9% as compared with 15% for the entire rotation. The average annual reduction in total runoff as percent of rainfall considering the 7 year period of the first rotation was found to be well comparable with the second rotation. It is worthwhile to mention here that these reductions in water yields during the first and second rotations were when the bluegum plantation covered only 59% (18.7 ha) of the watershed area (32 ha). Had the entire grassland been fully stocked with bluegum trees, the magnitude of reduction would have been much higher. The mean monthly observed total runoff during the first rotation (38.5 mm) was found to be 68% higher as compared with the second rotation (22.9 mm) and was statistically different at the 1% level of significance.

Fig. 3 shows the 95% prediction limits for the regression line between annual computed and observed total runoff values for the second rotation. Half of the annual values of runoff during the first rotation fall within the prediction limits and half outside the prediction limits with the mean of the runoff
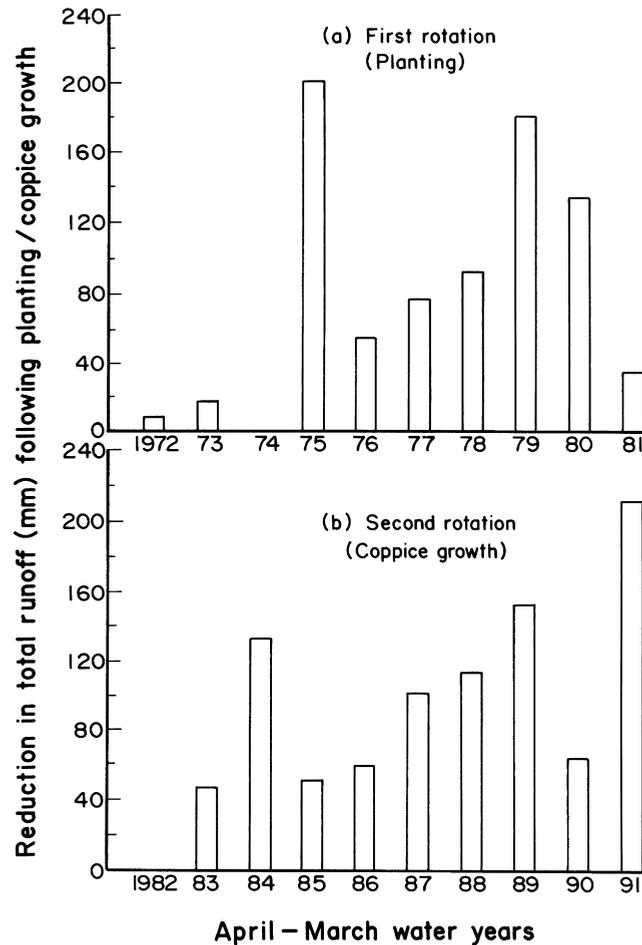
Fig. 2. Reduction in total runoff caused by bluegum during (a) the first rotation, and (b) coppiced growth.

values located just on the prediction limit. This implies that the difference in the runoff values of the two rotations is not statistically significant. The analysis of reductions in annual runoff values during first and second rotations using Student's *t*-test also confirmed that the difference in means of the reductions of two rotations was not statistically significant.

Rainfall–runoff (observed values) relationships for the planted watershed for the first and second rotations are presented in Fig. 4. The slopes of the regression lines are equal thereby confirming almost identical hydrological behaviour of the planted watershed during the two rotations. It was, therefore, inferred that for a given rainfall increment, the corresponding increase in runoff was equal in both the rotations. The coppiced bluegum, however, retained about

10 mm higher rainwater during second rotation as compared with the first which was ascribed to the rapid and vigorous growth of coppice shoots and higher biomass production. Consequently, the coppiced bluegum caused a further reduction in water yield as compared with first rotation. Fig. 5 shows the regression relationship between observed and computed total runoff values using monthly data during the first and second rotations. The deviation in runoff values between the two rotations increased with the increasing runoff. It can be inferred that effect of bluegum on water yield was more pronounced during the second rotation as for a given amount of runoff computed for the untreated case, the corresponding observed runoff for the treated watershed is lower during the second rotation as
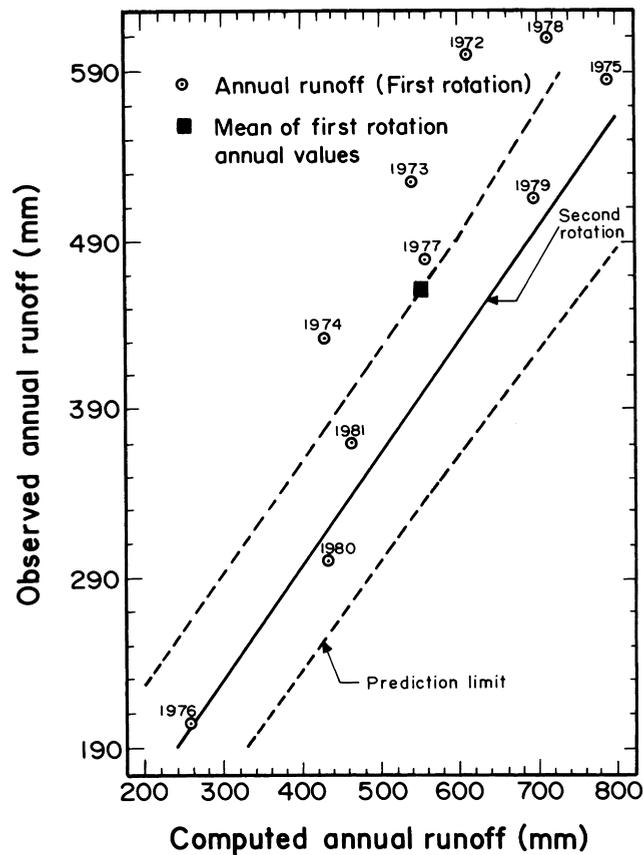
Fig. 3. Relations of computed and observed annual runoff from coppiced growth. Values of the first rotation are overlaid on the second rotation best fit line.

compared with the first rotation. The coppiced blue-gum, thus, brought about higher reduction in water yield during the second rotation which was in conformity with the rainfall–runoff relationships. A Similar trend in regression relationships was observed for the monthwise base flow values during the first and second rotations (Fig. 5).

4.1.4. Effect of clearfelling on water yields

Hydrological recovery after clearfelling of bluegum during the year 1982 at the end of first rotation (1972–81) is evident in Fig. 6. The computed total runoff (201.8 mm) in the clearfelled watershed B was well comparable to the observed runoff (201.1 mm) indicating thereby that the hydrological behaviour of the bluegum planted watershed was restored to the pre-planting conditions. The increase in surface runoff by 48% due to poor surface cover

under bluegum after clearfelling was compensated by a corresponding decrease in base flow by 14% such that the total runoff remained almost equal. In the year preceding clearfelling of bluegum (1981), a reduction of 20% in total runoff was observed. The hydrological recovery, however, lasted only for a year and in the subsequent year (1983), the rapid and vigorous growth of coppice shoots reduced the total runoff to the extent of 19%. A similar trend was observed during 1992 immediately after the harvest of coppiced bluegum (Fig. 7). The results were in agreement with the reported findings in the literature (Stoneman, 1993; David et al., 1994).

4.2. Soil moisture and ground water depletion

Statistically significant ($\alpha = 0.01$) mean monthly reduction of 2.4 cm year^{-1} in soil moisture up to
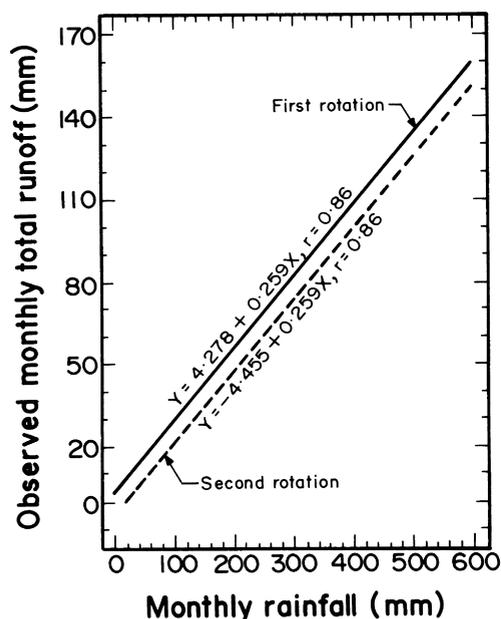
Fig. 4. Rainfall–runoff relationships for the planted watershed during two rotations of bluegum.

0.5 m sampling depth and 3 cm year^{-1} at 1 m depth during the second rotation was also recorded (Table 3). The comparison with the first rotation indicated that while the soil moisture depletion at 1 m depth was

significant at only 5% level of probability during the first rotation, the significance was observed at 1% level during the second rotation. It was concluded that during the second rotation, the extraction of moisture was not only confined to upper layers, but also extended to deeper horizons as a result of a more extensive root system. The higher moisture depletion during the second rotation was ascribed to fast and vigorous growth of coppiced bluegum and, in turn, higher biomass production.

Compared with a total mean monthly reduction of 45.6 cm in depth of water levels in swamps due to bluegum during the first rotation, the reduction during the second rotation was 49.4 cm. The statistical analysis, however, reveals that the reductions were significant only at 5% level during both the rotations implying thereby that bluegum did not interfere markedly with the water levels in the swamps. From the root analysis and ground water fluctuation data of the second rotation, it was observed that the tap root of the sampled trees penetrated to a maximum depth of 3.2 m whereas the highest water level in the piezometric wells during the monsoon season was at a depth of 4.6 m below the ground surface at the lowest contour of the bluegum plantations. The roots were, however, found to spread laterally up to a distance of
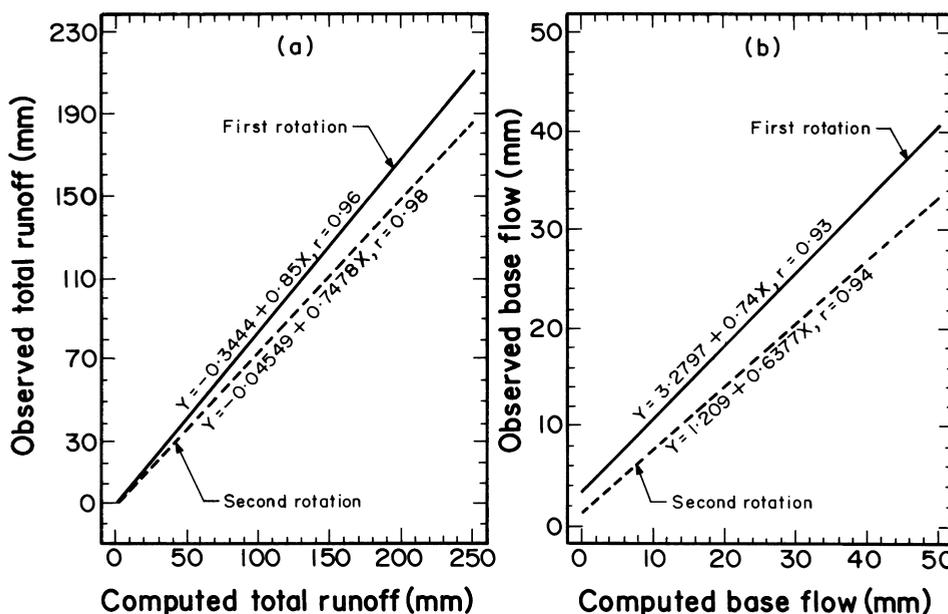

Fig. 5. Relations of computed and observed total runoff (a), and base flow (b), for the planted watershed during two rotations of bluegum.
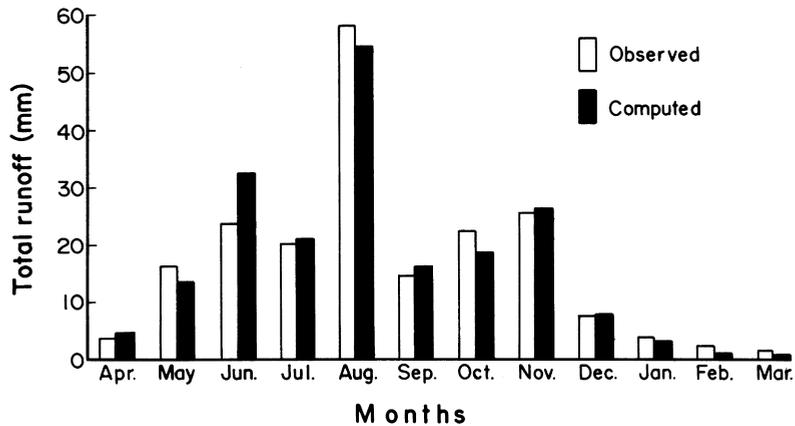
Fig. 6. Monthly observed and computed total runoff during 1982 just after clear felling of bluegum (first rotation) indicating hydrological recovery.

6 m and establishing a dense network in continuation to the first rotation. Hence, during the second rotation also, the roots do not directly interact with the phreatic surface.

5. Growth and economic analysis

The yearly progressive increase of height during the second rotation indicated that the coppice shoots attained maximum growth rates during the 2nd–7th years (1983–88), which is equivalent to 64% (11.1 m) of the total height attained during the rotation (Fig. 8). The DBH (diameter at breast height) also registered a maximum growth of 15.3 cm during this period which

works out to be 62% of the total growth during the second rotation. Compared with the first rotation, wherein the height increased steadily throughout the rotation period, the growth rate showed a significant decrease after the seventh year during the second rotation. The growth in DBH also followed a trend similar to variation in height. The higher values of height and DBH during the second rotation increased bio-mass production substantially. The total volume of pulpwood, for example, has increased by 42% during the second rotation (4810.1 m^3) in comparison to the first rotation (3391.3 m^3).

The coppiced bluegum plantations of the second rotation were harvested during July 1992, and were sold out separately for pulpwood and leaves. The total
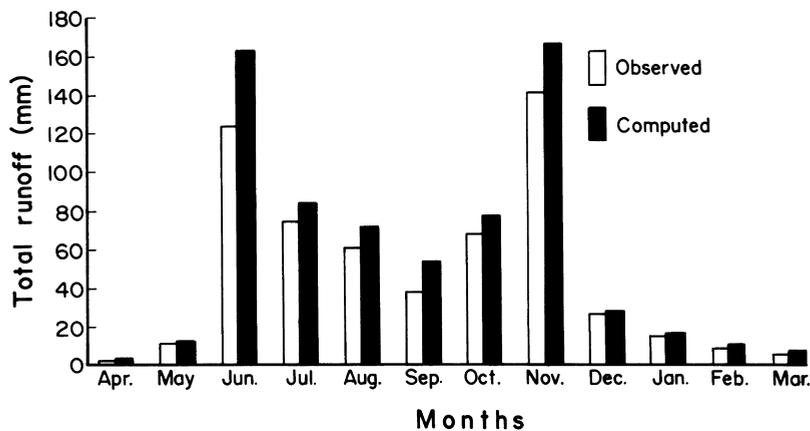

Fig. 7. Monthly observed and computed total runoff during 1992 just after clear felling of bluegum (second rotation) indicating hydrological recovery.

Table 3
Comparison of mean monthly soil moisture (cm) of grassed watershed with first and second rotations of bluegum planted watershed

Depth (cm)		*First rotation*											
		1972	73	74	75	76	77	78	79	80	81	Mean	(A-B)
50	A	18.6	18.4	21.6	21.8	16.8	13.9	13.1	12.2	14.1	14.5	16.5	
	B	17.7	17.6	19.6	19.6	15.8	12.3	11.6	12.1	13.6	13.3	15.4	1.1
100	A	—	—	—	—	30.6	23.1	29.2	26.1	27.1	23.0	26.5	
	B	—	—	—	—	26.1	22.5	25.8	25.8	25.7	22.2	24.7	1.8
		Second Rotation											
		1982	83	84	85	86	87	88	89	90	91	Mean	(A-B)
50	A	11.9	12.3	24.4	21.0	33.7	33.8	32.9	32.0	38.0	31.5	27.2	
	B	11.2	10.4	22.7	19.9	29.7	32.6	31.7	28.5	33.1	28.2	24.8	2.4
100	A	—	—	24.3	19.7	33.6	33.9	32.9	32.0	38.0	36.0	31.3	
	B	—	—	21.6	18.5	29.8	32.5	31.0	27.6	32.8	32.6	28.3	3.0

A, grassland watershed; and B, bluegum planted watershed.

income from pulpwood, leaves and rejects for the second rotation worked out as Rs. 4560 ha^{-1} year^{-1} (at the price level of 1982–83) as compared with Rs. 3250 ha^{-1} year^{-1} in the first rotation, thereby registering an increase of more than 40% over the first rotation.

6. Conclusions

The analysis of hydrological data during the second rotation revealed that coppiced bluegum significantly reduced total runoff (25.4%) and base flow (27%) as compared with natural grassland catchment. The maximum reduction occurred during the months July–October in which 60% of the mean annual rainfall was received. It is, therefore, inferred that the reduction in water yield as a result of bluegum is directly related to the availability of rain water during the year. During the low flow period (January–April), the water yield in the natural grassland catchment, was reduced by 28.6% by coppiced bluegum. This reduction, though quantitatively small, is very crucial for sustaining dry weather flow in hydro-electric reservoirs downstream.

In comparison to the first rotation, the coppiced bluegum produced relatively more adverse effect on water yield and other hydrological components. The mean monthly observed total runoff during the second
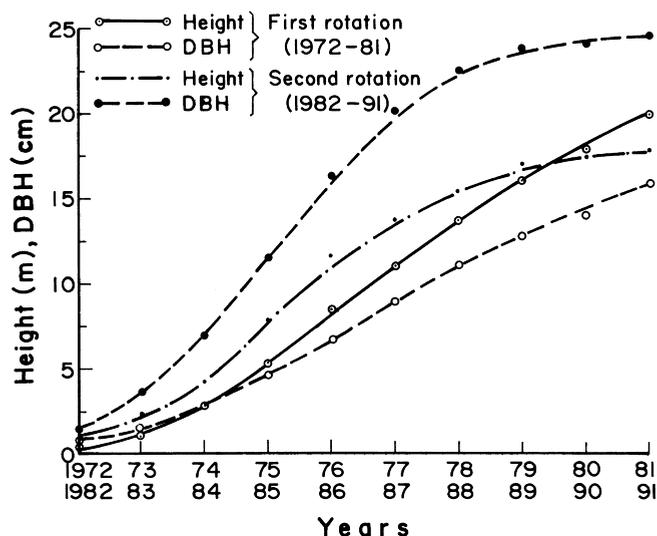

Fig. 8. Height and DBH of bluegum during the two rotations.

rotation was 68% lower than in the first rotation indicating higher reduction caused by the coppiced bluegum. The difference in the mean annual reductions in total runoff during the first and second rotations was, however, not statistically significant both at the 1% and 5% levels of probability.

The coppiced bluegum significantly ($\alpha = 0.01$) depleted the soil moisture upto 1 m depth as against 0.5 m during the first rotation. The higher moisture utilization by coppiced bluegum produced 42% higher biomass than the first rotation. Though the coppiced bluegum had a well developed root system, it had no direct contact with the groundwater table and remained well above it. It is concluded that maintaining bluegum as a coppice growth was profitable, but it adversely affected the water supply to the downstream hydro-electric reservoirs.

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