Water Authority
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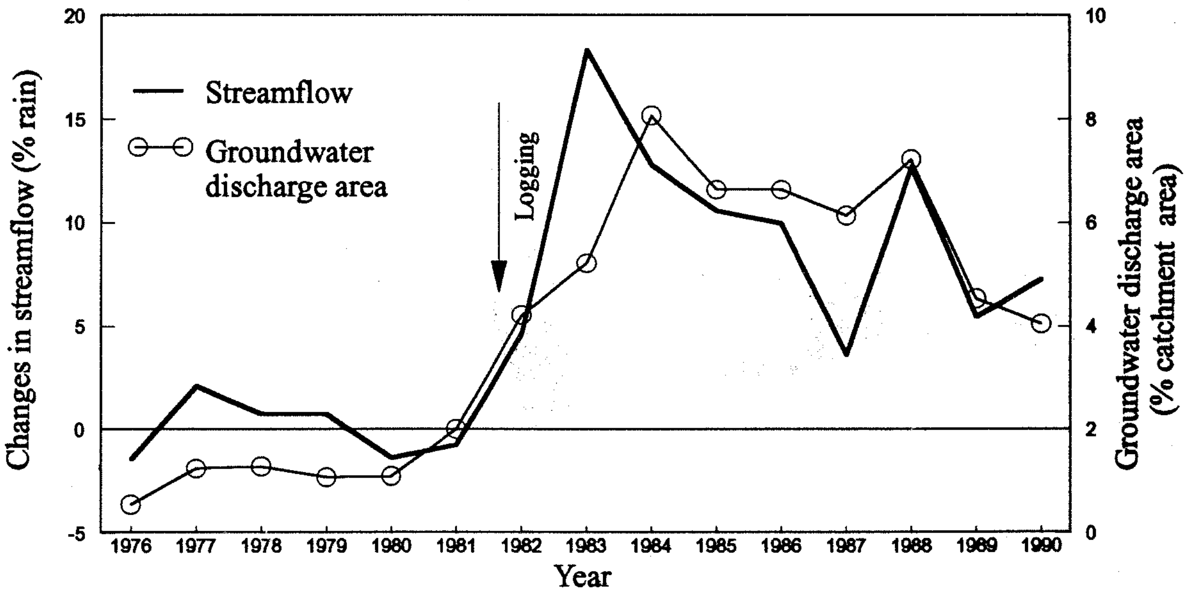
GENERATION OF STREAMFLOW FOLLOWING CLEARFELL LOGGING AND REGENERATION AT MARCH ROAD CATCHMENT



Report No. WS119
August 1994

Water Authority
of Western Australia

Water Resources Directorate
Surface Water Branch

GENERATION OF STREAMFLOW FOLLOWING CLEARFELL LOGGING AND REGENERATION AT MARCH ROAD CATCHMENT

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SUMMARY

The southern forest region of Western Australia contains 39% of the State's surface water resources. Timber has been logged in this region for more than 100 years. In 1960's the Department of Conservation and Land Management (CALM) changed the forest management method to heavy selection cutting and clear felling. It raised concern among various conservation groups and the community that changes in forest management method may alter the hydrological balance and lead to substantial increase in stream salinity.

The impact of logging and subsequent regeneration on the process of streamflow generation has been studied on two small forested catchments in the south-west of Western Australia. Following 6 years (1976-81) of pretreatment calibration period, one catchment (March Road) was logged and reforested in 1982 and the other (April Road South) remained as a control.

Logging resulted in an increase in groundwater levels and groundwater discharge area. On the treated catchment, permanent groundwater levels in valley and upslope areas increased until 1987 and then began to decline. The maximum increase was 4.5 m in the valley. Shallow, intermittent groundwater systems, perched on underlying clay, were present in the catchments. Prior to logging a shallow groundwater system was evident for 2-3 months in winter which was present for 5-6 months after logging. Depth to the shallow groundwater systems in the valley decreased following logging and began to discharge at ground surface in 1984.

Logging resulted in an increase in streamflow. The maximum increase (~18% of annual rainfall) was in 1983. The increase in streamflow was due to a substantial decrease in evapotranspiration, increased recharge to the shallow groundwater system and decreased soil moisture deficit. The increase in base flow was about twice that of quick flow. The changes in streamflow and its components in the subsequent years were closely related to the groundwater discharge area. Most of the quick flow was generated as saturation excess overland flow from the groundwater discharge area in the valley. The expansion of the groundwater discharge area, increased soil moisture content, higher water level and the presence of the shallow groundwater system for the extended periods were attributed to the process of streamflow generation.

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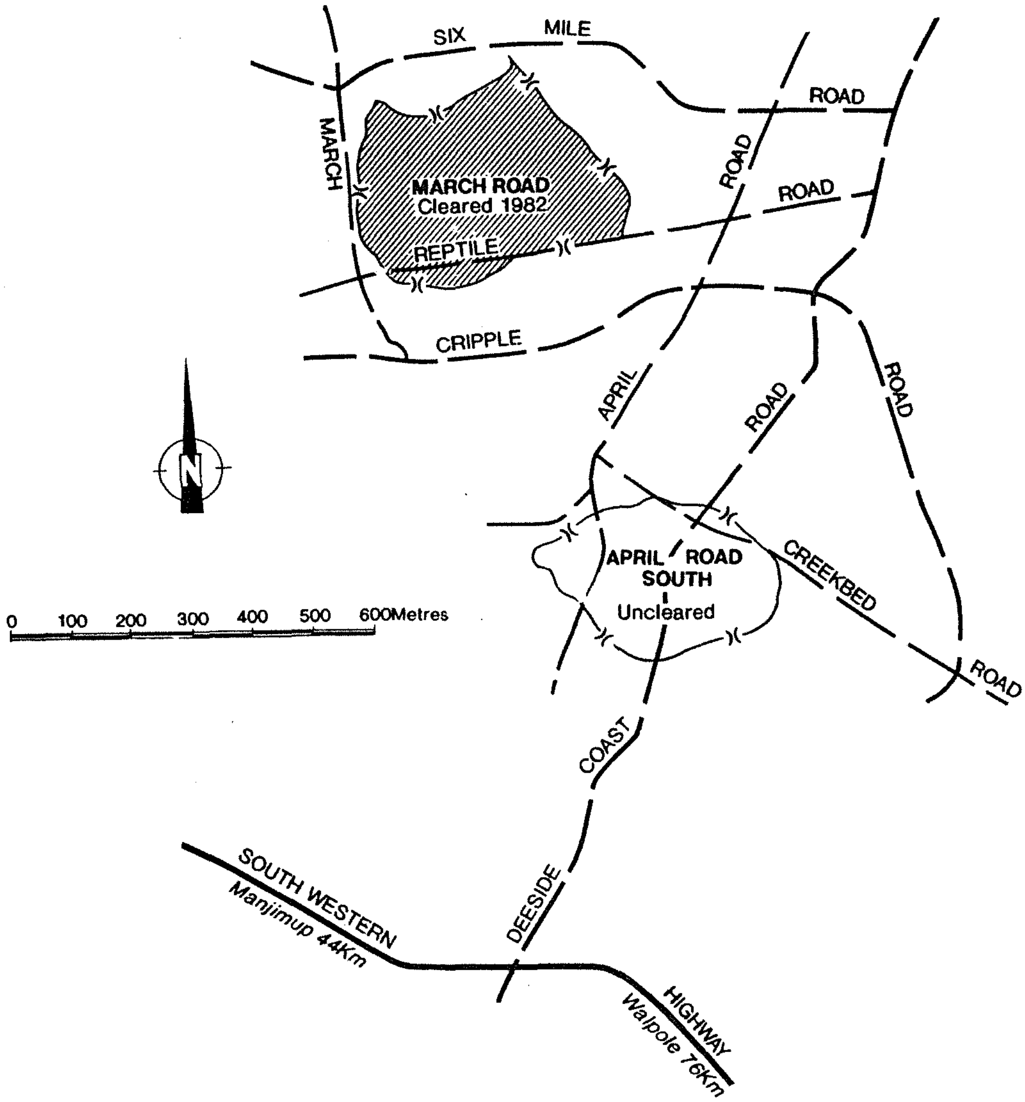
1 INTRODUCTION

It is now well established that changes in catchment vegetation cover effect streamflow (Bosch and Hewlett, 1982; Cornish, 1993; Hornbeck et al., 1993; Jayasuriya et al., 1993). The removal of native forest reduces interception and transpiration. More water becomes available to increase soil moisture content and groundwater recharge (Sharma et al., 1987a). The reversal of this hydrologic disturbance depends upon the growth of the regeneration (Borg et al., 1988; Bari and Boyd, 1993).

Several studies in Western Australia have researched the relationship between changes in forest cover and streamflow. These projects include: (a) the effects of catchment clearing for agricultural development (Ruprecht and Schofield, 1989), (b) forest thinning for water production (Ruprecht et al., 1991; Stoneman, 1993), (c) bauxite mining and rehabilitation (Ruprecht et al., 1992; Ruprecht and Stoneman, 1993) and (d) partial reforestation for stream salinity control (Bari, 1992a,b). These experiments focus primarily on the relationship between streamflow yield and vegetation cover, not on the process of streamflow generation. It has been found that in a forested catchment a major part of streamflow is generated as throughflow from perched groundwater systems. Overland flow and deep groundwater flow only make minor contributions (Stokes and Loh, 1982; Loh et al., 1984; Stokes, 1985; Turner et al., 1987).

In 1976, three sets of experimental catchments were established in the southern forest of Western Australia. These experimental catchments are located in the High, Intermediate and Low Rainfall Zones. The main objective of the research was to determine long term effects of logging and subsequent regeneration on streamflow and salinity. Streamflow and salinity data collected from these experimental catchments have recently been analysed and reported by Bari and Boyd (1993). It was found that following logging and regeneration, contributions from each of the streamflow components change to provide greater streamflow. However, it is not clearly understood which streamflow components provide the greatest increase in streamflow.



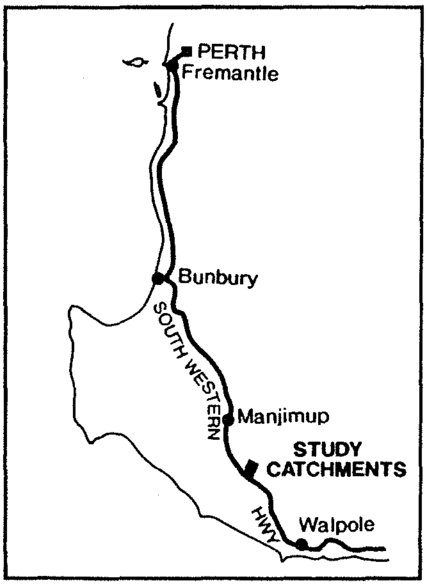


Figure 1 Location of the study area

The two study catchments (March Road and April Road South) are located in the Intermediate Rainfall Zone (900-1100 $mmyr^{-1}$) (Fig. 1). Extensive hydrological data were collected from these catchments to determine the effects of logging and subsequent regeneration on the process of streamflow generation. The analyses are based on the hydrological data collected before, during and after forest treatment in 1982.

2 SITE DESCRIPTION

The paired catchments, March Road and April Road South, are located in the south-west of Western Australia, about 300 km south of Perth (Fig. 1). The region has a Mediterranean climate, with cool, wet winters (June-August) and warm to hot dry summers (December-February). The long term annual rainfall of the catchments were estimated to be 1050 mm yr^{-1} (Loh and King, 1978) while the annual pan evaporation was 1300 mm yr^{-1} (Luke et al., 1988).

March Road has a catchment area of 261 ha. The elevation of March Road ranges from 170 to 230 m Australian Height Datum (Fig. 2). The soil types are typical of the south-west of Western Australia, consisting mainly of laterite, red earths and yellow duplex soils. The soil profile typically consists of a 30-100 cm of highly permeable soil on top of 5-20 m of clay with low permeability. The average saturated hydraulic conductivity of surface soils was measured at 2.5 m day^{-1} in 1992. Prior to logging, the native forest was dominated by jarrah (*Eucalyptus marginata*), marri (*E. calophylla*) and karri (*E. diversicolor*).

The topography, soil, geology and vegetation of the control catchment (April Road South) are similar to the March Road catchment.

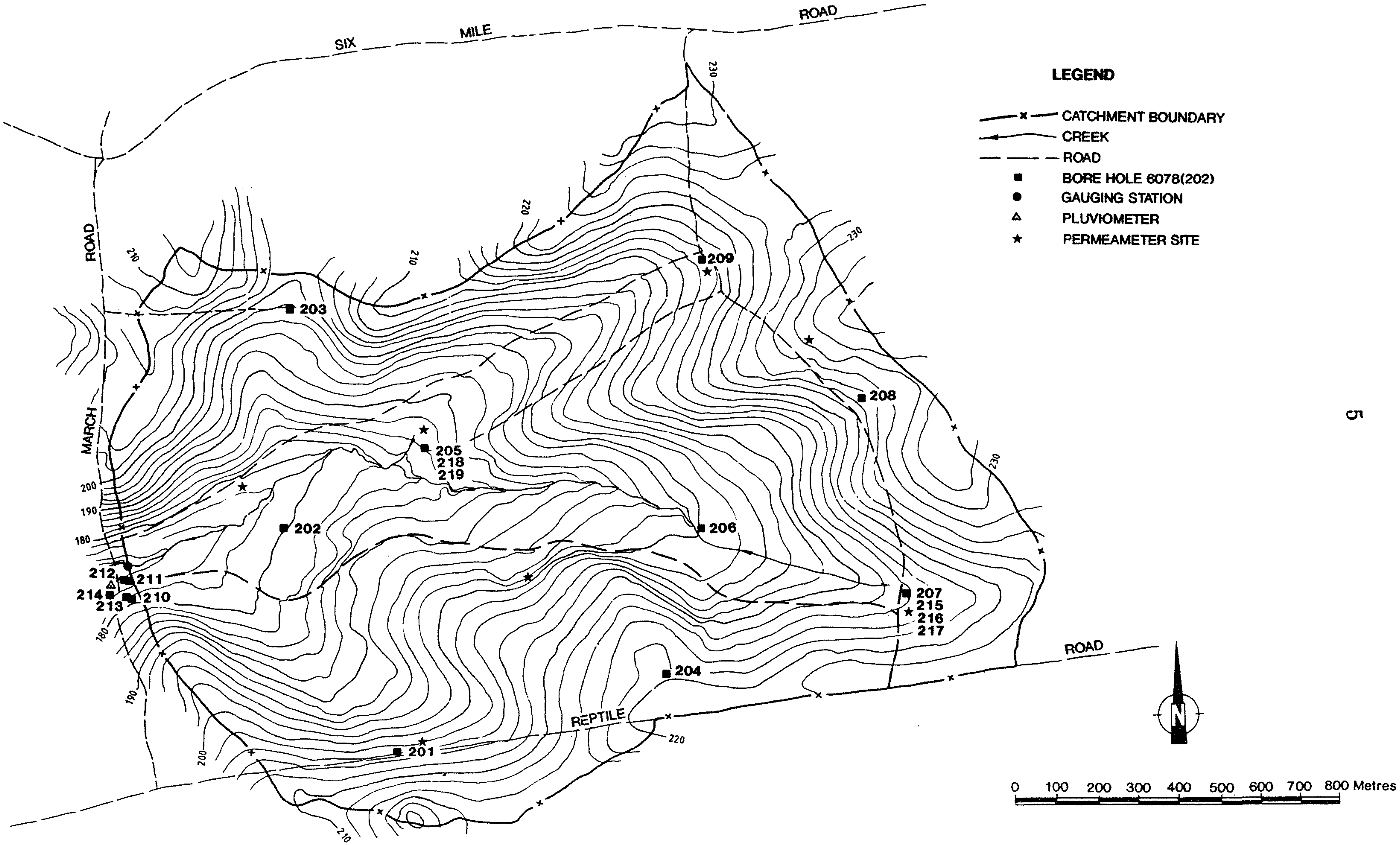


Figure 2 **March Road Catchment map with experimental setup**

3 EXPERIMENTAL METHOD AND INSTRUMENTATION

3.1 Experimental Method

The experimental method was paired catchment approach, one being treated and other remaining as control. In 1976, March Road and April Road South catchments were established and in 1982 March Road was treated by clear felling with April Road South remaining as control. The regression equations for streamflow and its components for March Road and April Road South catchments were determined for the pretreatment period. These regression equations were applied to the post treatment data of April Road South to obtain streamflow yield and its components at March Road as if it had remained forested. This procedure provided control over climatic variation.

The hydrological effects of logging and regeneration were assessed by comparing the differences between the predicted and observed data for March Road.

3.2 Instrumentation and Measurements

Both catchments had similar monitoring networks. **Rainfalls** were recorded by pluviometers located at the catchment outlets (Fig. 2).

To monitor **streamflow**, sharp-crested V-notch measurement structures were constructed at the outlets of the catchments and instrumented to supply continuous record of stage (water level). Streamflow data was derived by the application of a discharge rating curve.

A network of 19 bores were drilled to monitor the shallow (<2 m) and deep (>2 m) **groundwater systems** of the catchments. Observation bores were installed to cover the valley, midslope and upslope areas (Fig. 2). Most of the bores were monitored for groundwater level once a month. Saturated hydraulic conductivities were measured in 1992 at March Road (Fig. 2) and April Road South using a constant head well permeameter (Bell and Schofield, 1990).

3.3 Catchment Treatment

Logging commenced at March Road catchment in January 1982. Logging continued throughout the wet season and the whole catchment was cleared by March 1983 (Fig. 3). All the merchantable timbers were removed from the catchment and waste disposals were heaped and burnt. Nursery raised karri seedlings were hand planted in 1983. The forest cover at April Road South remained intact during the period of investigation.

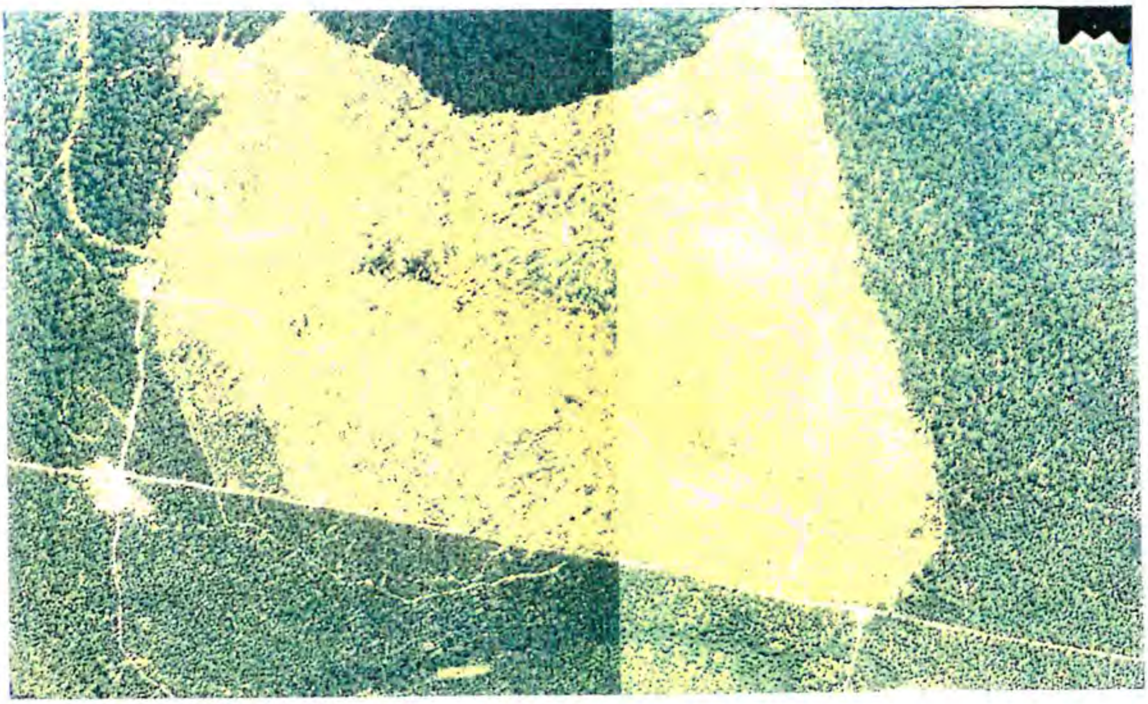


Fig. 3 Photograph of March Road catchment showing clearfelling

4 RESULTS

4.1 Vegetation Response

Before logging, the total and over storey vegetation covers at both catchments were the same, 90% and 65% respectively (Stoneman et al., 1988). Clear-felling of native forest at March Road catchment reduced vegetation cover to nil. Vegetation started to regenerate immediately after logging and planting. By 1991, the total and over storey vegetation covers at March Road catchment increased to 91% and 79% respectively (Bari and Boyd, 1993). Fig 4 shows the catchment vegetation cover as at January 1991.

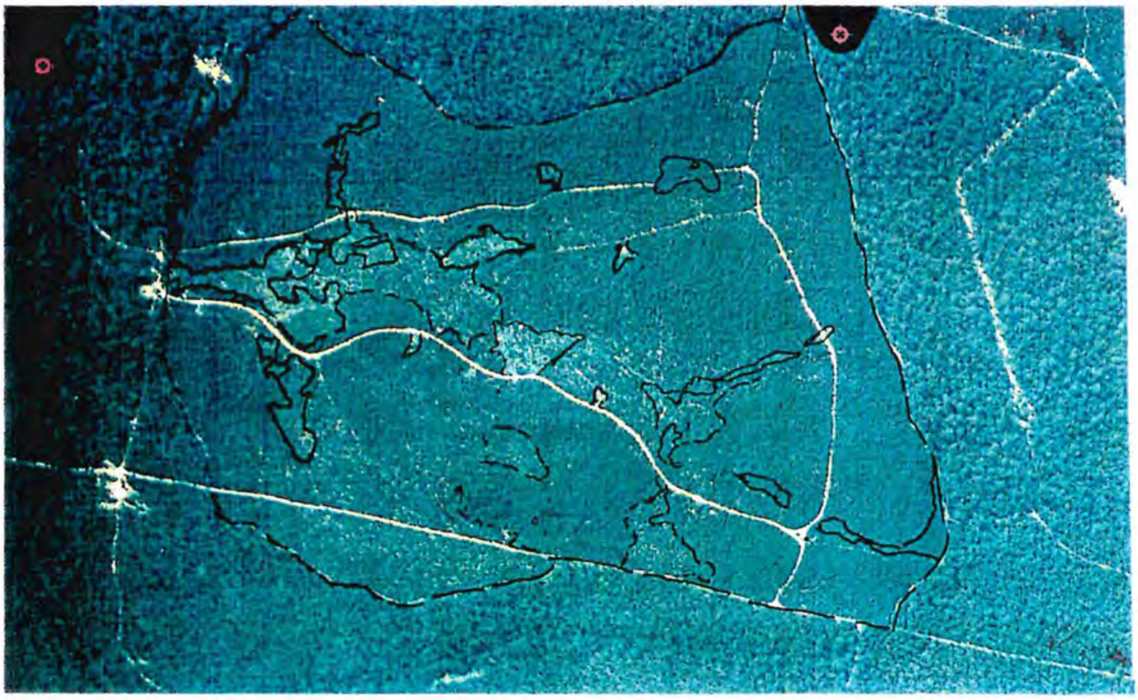


Fig. 4 Photograph of March Road catchment showing regeneration in 1991

4.2 *Annual Rainfall*

During the study period (1976-91), the average annual rainfall was 10% lower than the long term average (1926-76) of 1040 mm (Table 1). However, in 3 of the 16 years observed the annual rainfall was significantly higher than the long term average.

4.3 *Deep Groundwater Response*

4.3.1 Groundwater levels

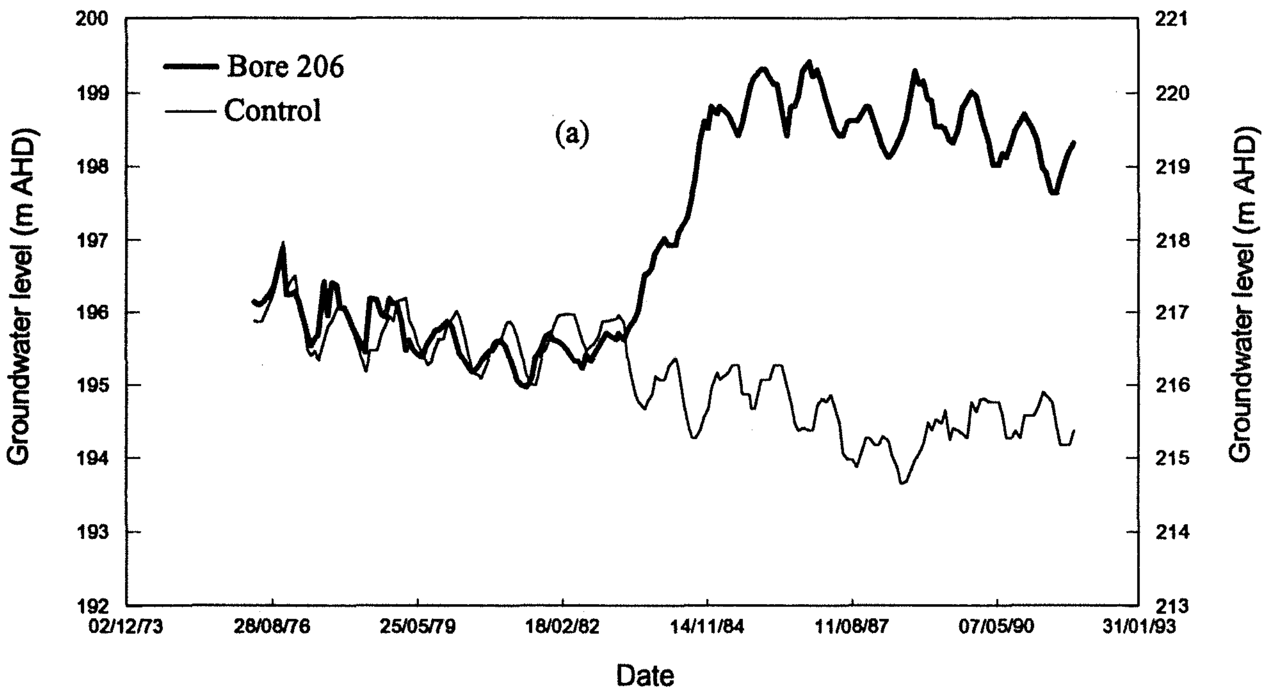
Prior to logging (1976-81), the groundwater trends in the upslope and valley areas at both catchments were similar. The depth to groundwater level at March Road catchment was about 20 m in the upslope and discharged at the surface in the valley areas. Groundwater levels in the valley and upslope areas showed similar trends (Fig. 5) during the pretreatment period (1976-81). Following logging in 1983, groundwater level rose at the treated catchment, in the valley and upslope areas. The maximum rise in groundwater level, compared to the control, was 4.5 m in the valley (Fig. 5a) and 5 m (Fig. 5b) in the upslope areas. Groundwater level in the valley started to fall in 1989 (Fig. 5), whereas the groundwater level in the upslope areas remain at the maximum level.

4.3.2 Groundwater discharge area

The groundwater discharge area was defined as the area where groundwater level was at or above the natural surface and was determined using annual minimum groundwater levels. A groundwater discharge area covering 1% of the catchment area was evident (Fig. 6a) in the valley. Following logging, the groundwater discharge area increased, peaking in 1984 at 8% of the catchment area (Fig. 6a). As the vegetation regenerated the area of groundwater discharge contracted. By 1990 the groundwater discharge area covered 4% of the catchment area which was 3% greater than prelogging levels (Fig. 6b).

Table 1 Changes in annual streamflow components following logging at March Road catchment

Year	Rainfall (mm)	Streamflow (mm)			Predicted streamflow (mm)			Changes in streamflow (% rain)		
		Total	Quickflow	Baseflow	Total	Quickflow	Baseflow	Total	Quickflow	Baseflow
1976	824.0	36.4	8.5	27.9	50.5	11.0	39.4	-1.71	-0.31	-1.40
1977	994.2	97.7	20.5	77.2	76.6	15.7	60.9	2.13	0.48	1.64
1978	1081.9	171.9	36.3	135.6	163.7	33.7	130.1	0.76	0.24	0.51
1979	879.1	63.9	13.2	50.7	57.2	11.8	45.4	0.76	0.16	0.61
1980	934.7	68.2	13.4	54.8	80.9	16.8	64.2	-1.36	-0.36	-1.01
1981	1230.0	165.7	29.7	136.0	174.8	32.7	142.4	-0.73	-0.24	-0.52
1982	720.2	60.6	13.4	47.2	27.1	4.2	23.0	4.65	1.27	3.37
1983	918.4	230.1	66.7	163.4	61.6	9.6	52.2	18.34	6.21	12.11
1984	1101.1	290.6	84.5	206.2	149.9	28.5	121.7	12.78	5.08	7.67
1985	992.2	149.1	43.7	105.5	44.4	8.5	36.0	10.56	3.55	7.00
1986	729.6	97.4	22.4	75.0	24.7	3.6	21.2	9.96	2.58	7.37
1987	757.8	34.8	10.6	24.2	7.56	-0.0	8.1	3.59	1.45	2.12
1988	1376.7	337.2	99.6	237.6	162.6	31.5	131.4	12.68	4.95	7.7
1989	983.9	131.5	30.3	101.3	77.8	12.3	65.8	5.46	1.82	3.60
1990	952.7	132.7	34.8	97.9	63.6	11.7	52.0	7.26	2.42	4.82
1991	1118.5	102.4	18.0	84.5	135.7	24.2	111.8	-2.97	-0.56	-2.44



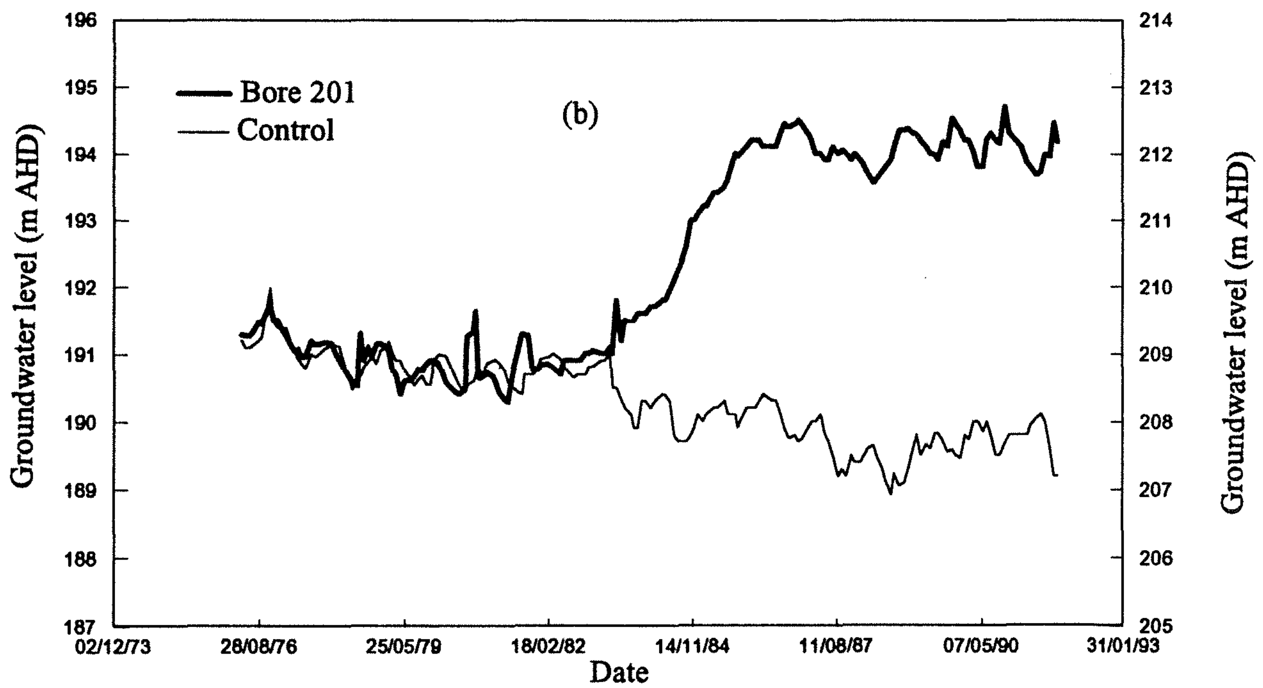


Fig. 5 Response of groundwater levels (a) valley, (b) upslope at the treated and control catchments

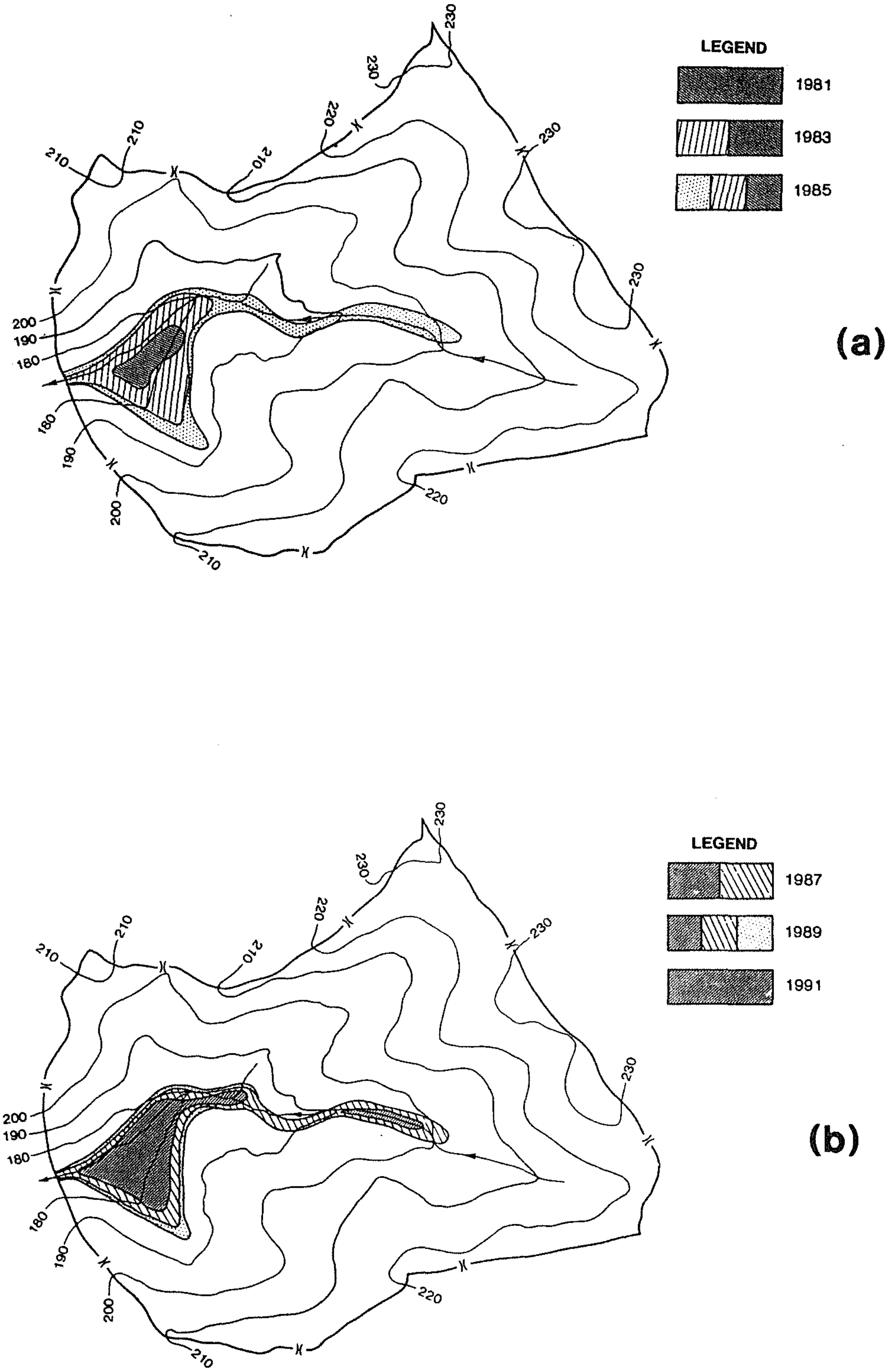


Figure 6 Groundwater discharge area at March Road Catchment during (a) 1981–85 (b) 1987–91

4.4 Shallow Groundwater Response

A shallow (0-2 m thick), intermittent, groundwater system, perched on cap rock or underlying clay, exists in March Road catchment. The shallow groundwater system existed for 2-3 months in winter (Fig. 7) during the pretreatment period. As a result of logging, depth to the shallow groundwater system reduced, which increased the presence of the system to 5-6 months each year. By 1986, the shallow groundwater system began to discharge at the surface causing an increase in groundwater discharge area (Fig. 7).

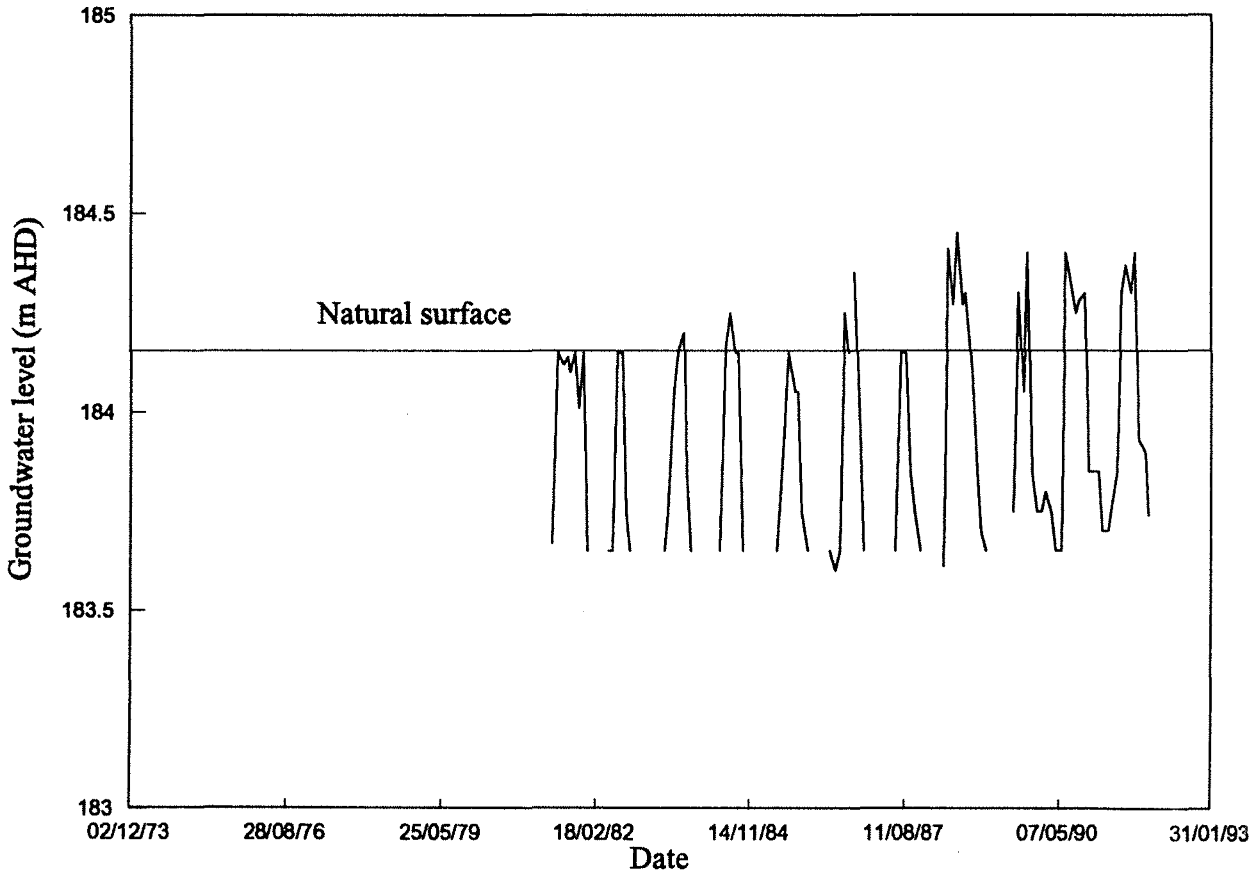


Fig. 7 Response of shallow groundwater level at March Road catchment

4.5 Streamflow

Prior to logging, March Road and April Road South catchments would start to flow in June/July and cease in November or early December. Both catchments had similar streamflow duration and magnitude (Fig. 8a). Due to less interception and transpiration after logging in 1983, March Road started to flow before the control site. When both catchments were flowing, there were considerable differences in the magnitude of peak flow (Fig. 8b). As vegetation grew back, streamflows at the treated and control catchments became similar but the peak flow still remained higher in the treated catchment(Fig. 8c).

A linear relationship developed between annual streamflow and rainfall (Fig. 9) for the pre-treated March Road catchment indicates runoff would not occur for an annual rainfall of 710 mm or less. However following logging, there had been a considerable increase in annual streamflow for a given rainfall. In 1983, 1984 and 1988, streamflows were significantly higher than what would have been without logging (Fig. 9).

A regression equation for annual streamflow between March Road (Y_s, mm) and April Road South (X_s, mm) during the pretreatment period (1976-81) has been developed (Fig. 10). The equation is:

$$Y_s=0.78X_s+4.43 \qquad r^2 = 0.94, n=6, p\sim 0.001 \qquad (1)$$

The regression equation was used to predict streamflow at March Road for the period 1982-91 as if there had been no logging and regeneration.

By comparing observed and predicted values, the hydrological effects of forest clearing and subsequent regeneration were assessed (Table 1). The maximum increase in streamflow was 18% of annual rainfall. After 1983, the increase in streamflow began to decline. There was a rise in 1988 due to above average rainfall in that year. In 1991, the annual streamflow was less than that predicted for forested conditions (Table 1).

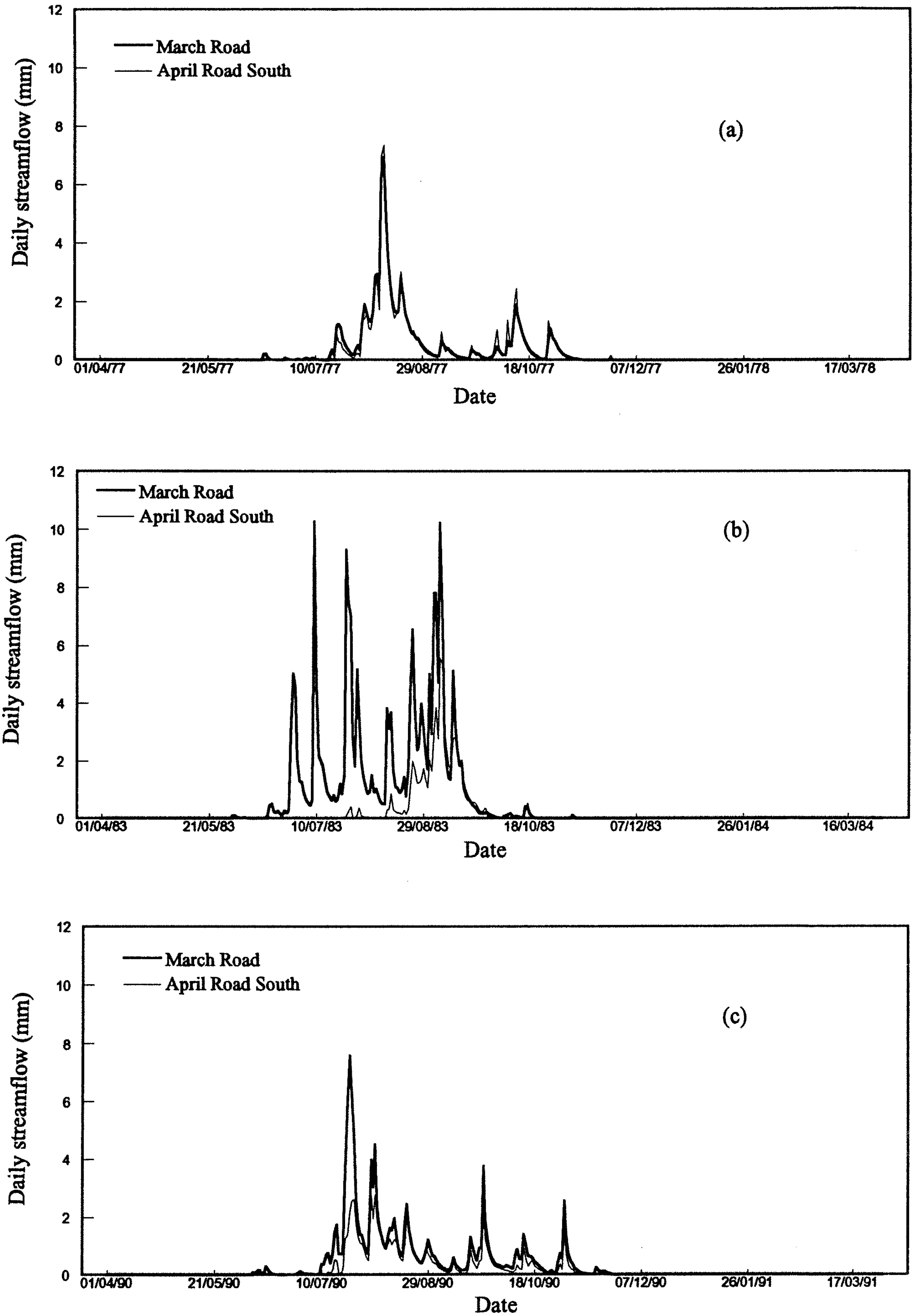


Fig. 8 Daily streamflow hydrographs at March Road and April Road South for (a) 1977, (b) 1983 and (c) 1990

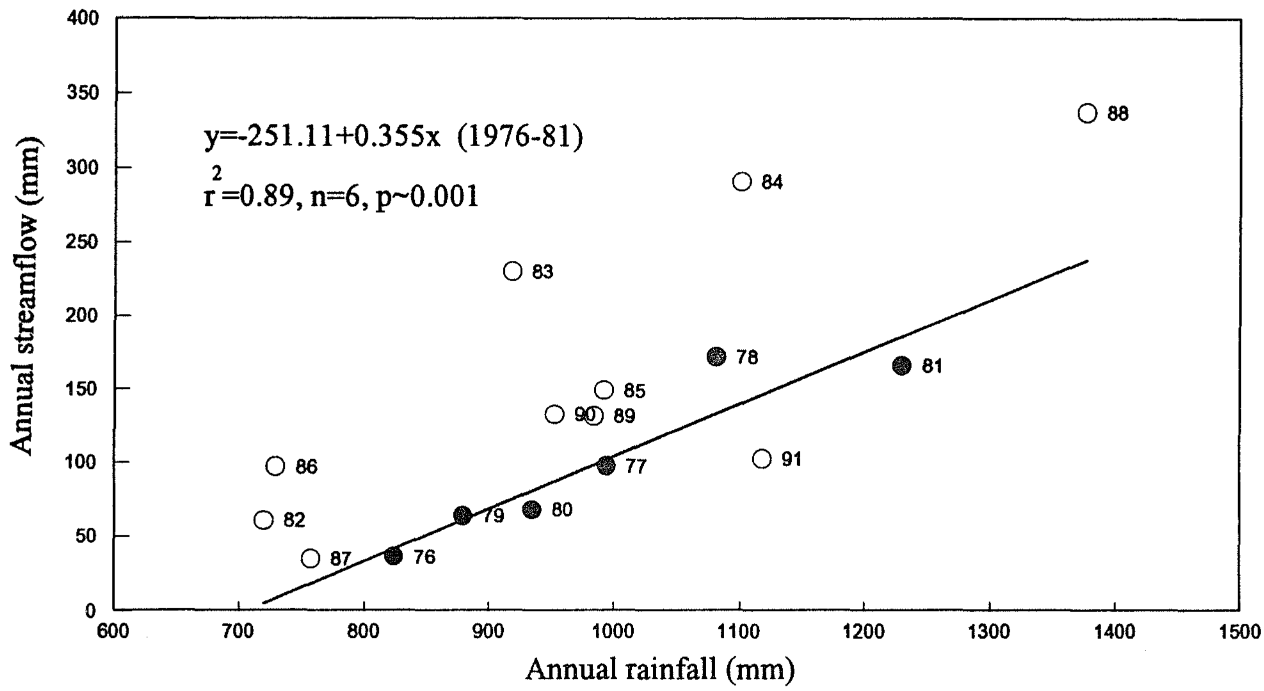


Fig. 9 Rainfall and streamflow relationship for March Road catchment

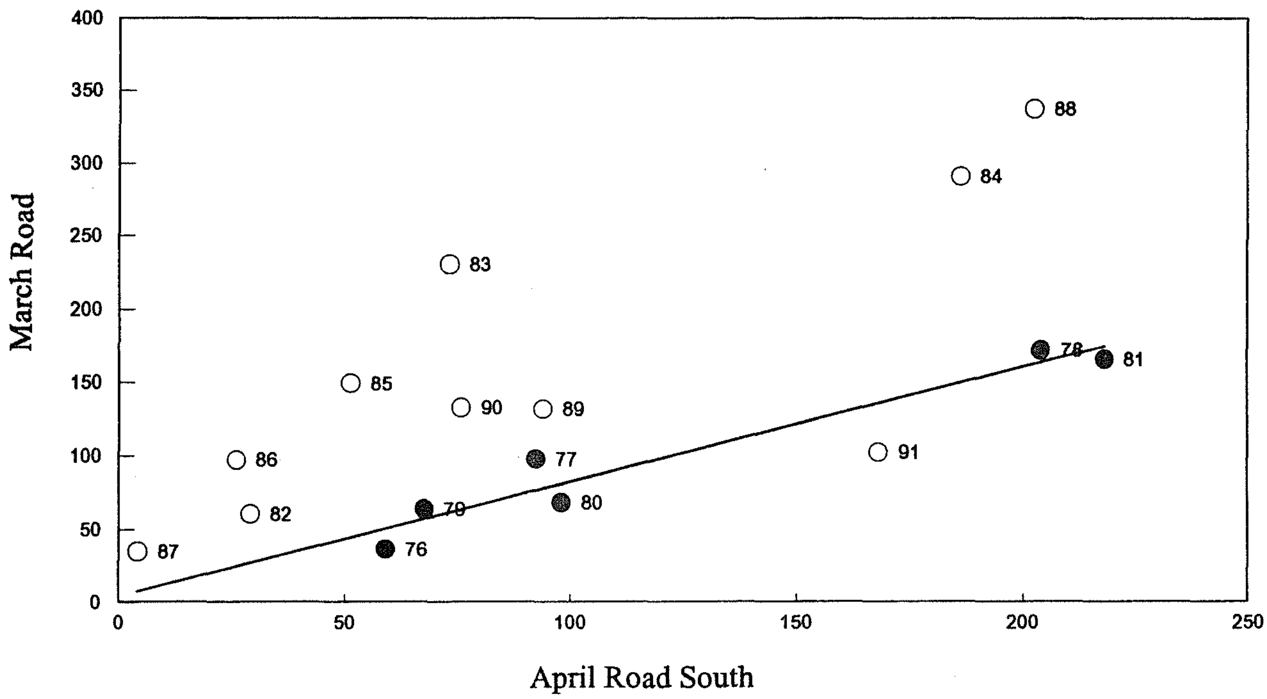
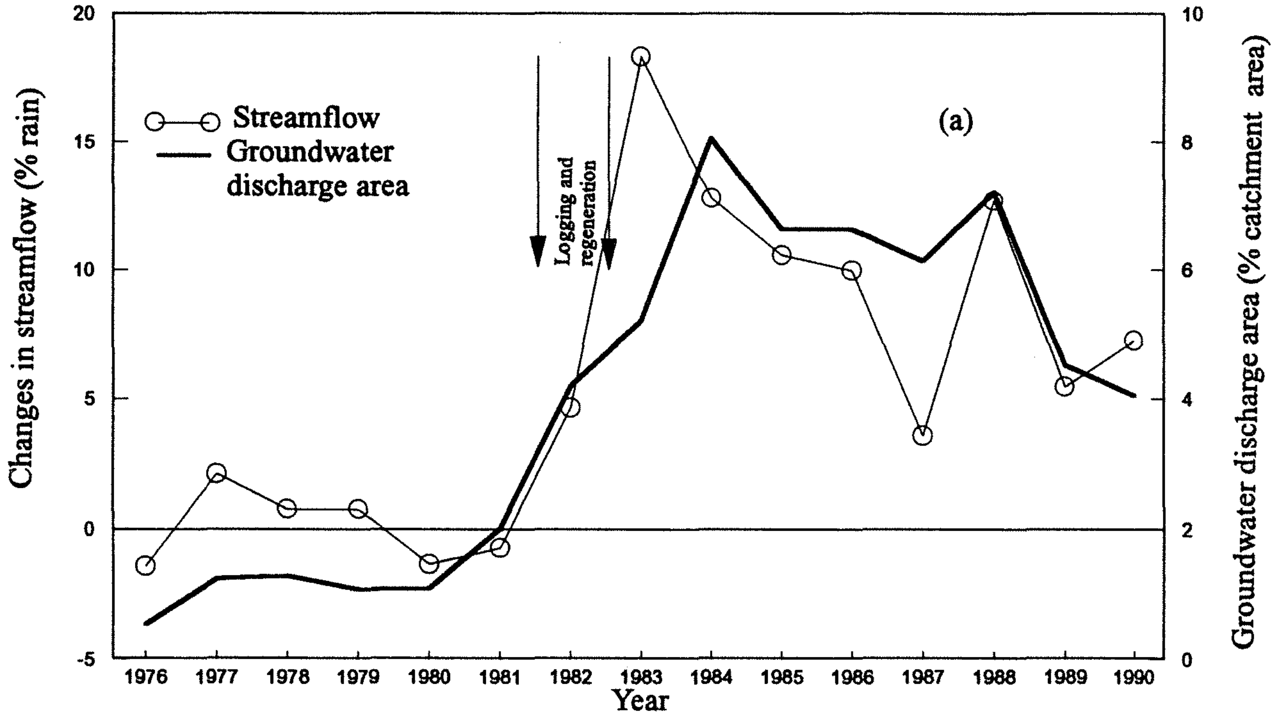


Fig 10 Relationship between annual streamflows at March Road and April Road South



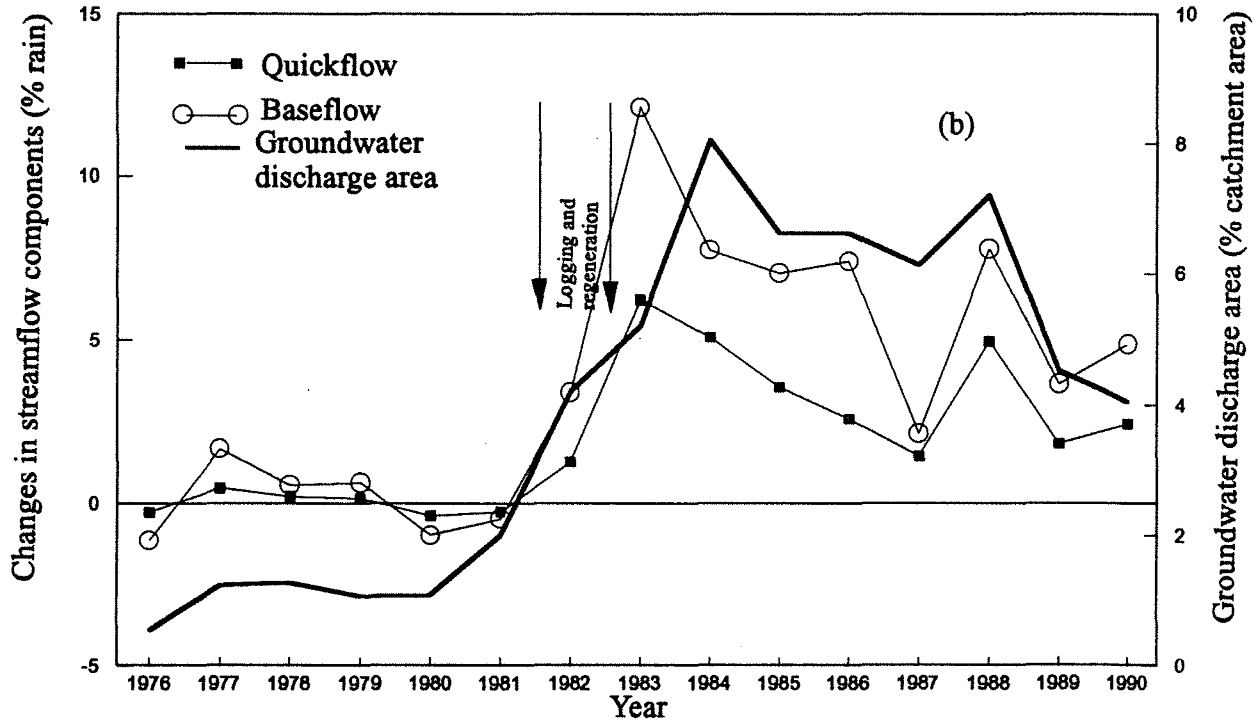


Fig. 11 Relationship between groundwater discahrge area and (a) streamflow, (b) quickflow and baseflow for March Road catchment

The daily streamflow was separated into quick flow and base flow components using the base flow separation algorithm developed by Lynne and Hollick (1979). The regression equations between March Road (Y, mm) and its control (X, mm) for the pretreatment period are:

$$Y_q=0.74X_q-1.73 \qquad r^2 = 0.90,\ n=6,\ p\sim0.001 \qquad (2)$$

$$Y_b=0.79X_b+6.32 \qquad r^2 = 0.94,\ n=6,\ p\sim0.001 \qquad (3)$$

where subscripts q and b represent quick flow and base flow respectively. Both the quick flow and base flow components peaked immediately after logging, increasing by 6% and 12% respectively, and then have generally decreased since, except for a temporary increase in 1988 (Table 1).

The trends of change in groundwater discharge area and annual streamflow show a strong relationship (Fig. 11a). The groundwater discharge area peaked in 1984, one year after the maximum increase in streamflow. Since 1985, the groundwater discharge area and increase in streamflow have showed similar trends. However, streamflow increased in 1990 while the groundwater discharge area contracted. The increase in quick flow and base flow components are also related to the changes in groundwater discharge area (Fig. 11b). This evidence suggests the area of groundwater discharge has a major influence on streamflow generation following logging and subsequent regeneration.

5 DISCUSSION

5.1 Groundwater Level

After logging, groundwater levels at March Road catchment increased due to an increase in groundwater recharge brought about by reduced interception and transpiration. In the valley along the stream lines, groundwater recharge was further enhanced by increasing lateral flow from upslope. As a result, groundwater discharge area (Fig. 6a) and groundwater level (Fig. 5a) increased in the valley. During 1982-84, groundwater level increased considerably in valley and upslope areas. There was very little seasonal variation (Fig. 5) due to the lack of interception and transpiration by the young trees. However, since 1985 seasonal variations in groundwater level became evident which implies evaporation and transpiration had increased (Fig. 5). Since 1986, valley groundwater levels began to fall (Fig. 5a) possibly as a result of increased water uptake by regenerating trees. However, the fall in groundwater levels was less evident in the upslope areas (Fig. 5b) where groundwater is generally below the root zone ($>$10 m) and recharge was still possibly taking place due to above average rainfall in 1988 and 1991.

Fig. 7 gives some indication of the seasonal discharge areas of the shallow groundwater systems. After logging, groundwater level in bore 219 increased. Positive piezometric heads in the winters of 1983, 84, 86 and 88 to 91 indicate the groundwater discharge area expanded during winter, was evident for 5 to 6 months and contracted during summer (Fig.6).

5.2 Streamflow Generation

Following the logging and regeneration of March Road catchment, there had been a reduction in interception and transpiration, a rise in deep and shallow groundwater levels, an expansion in groundwater discharge area, and an increase in streamflow duration and magnitude. The changes in daily streamflow (Fig. 8b) can be explained by a reduction in the soil water deficits at March Road compared to April Road South. In a similar catchment Sharma et al. (1987a) found that soil water content increased down to a depth of 6 m after clearing of native vegetation for pasture development. A similar increase in soil moisture content was expected at March Road. The lower soil water deficit meant less rainfall was required to commence streamflow at March Road. However, after considerable rainfall in winter, the difference of soil water deficits between control and the treated catchments was negligible as evidenced by the similar streamflow hydrographs (Fig. 8b). As vegetation regenerated, the hydrographs for both catchments became similar (Fig. 8c). However, the peak flows at March Road catchment remained high due to increased overland flow from the ground water discharge area, an increase in soil water content and the associated throughflow (Ruprecht and Schofield, 1989).

The streamflow increase was a result of an increase in both base flow and quick flow components (Fig. 11). The increase in the quick flow component could be attributed to an increase in infiltration excess overland flow and/or saturation excess overland flow. The hydrogeology of both catchments were similar under forested conditions (Martin, 1987). But the spatial average saturated hydraulic conductivity for March Road (2.5 m day^{-1}, measured in 1992) was considerably lower than for April Road South (6.5 m day^{-1}). This suggests that logging had a significant long term impact on the hydraulic conductivity of surface soil. In a cleared catchment with similar hydraulic conductivities and annual rainfall to March Road, Sharma et al. (1987b) concluded that the chance of infiltration excess overland flow is very small because rainfall intensity rarely exceeds the infiltration capacity of the soil. The strong relationship between the discharge area and the quick flow (Fig. 11b) indicates that it is a result of saturation excess overland flow from the discharge area. However, there may be a seasonal fluctuation in the discharge area. This is supported by the seasonality of the shallow groundwater level in bore 219 which is located close to the groundwater discharge area (Fig. 2).

Base flow also showed a strong relationship with the groundwater discharge area (Fig. 11b). The base flow component is composed of throughflow and groundwater flow. The throughflow component is defined as the water perched on the low conductive clay layer (shallow groundwater system) which flows downslope into the stream. Throughflow makes up 60 to 80% of streamflow while the quick flow and deep groundwater flow components are minor contributors (Stokes and Loh, 1982; Stokes, 1985; Turner et al., 1987; Ruprecht and Schofield, 1989). The throughflow component is very sensitive to annual rainfall while the groundwater flow is almost independent (Bari, 1992a). There are insufficient data to quantify the changes in throughflow and deep groundwater flow components in this study. However, Sharma et al. (1987a) found an increase in soil water content following agricultural clearing. Similar results are also expected from March Road. The probable increase in soil moisture content, higher groundwater level, greater extent of groundwater discharge area and persistent rise in shallow, perched groundwater level over time (Fig. 7) indicate an increase in throughflow since logging in 1982.

Streamflow and its components peaked in 1983 while the area of groundwater discharge peaked a year later (Fig. 11). Clearing has an immediate impact on interception and transpiration. Williamson et al. (1987) found a 13% decrease in the interception of annual rainfall following clearing of native forest. Following logging the additional available water causes a direct and immediate increase in recharge to the shallow groundwater system leading to increased throughflow. Therefore, the initial (maximum) increase in streamflow and its components (Fig. 11) was due to increased throughflow. However, the subsequent streamflow increase was closely related to the groundwater discharge area (Fig. 11). That means the groundwater discharge area played an important role in the streamflow generation following the initial rise in 1983. A similar relationship between streamflow increase and the groundwater discharge area was also found by Ruprecht and Schofield (1989).

5.3 Vegetation Regeneration and Streamflow

As native vegetation regenerates evapotranspiration and interception increases and thereby decreases groundwater recharge. Results from this study indicate that as vegetation regenerates all streamflow components decrease and deep groundwater stops rising and starts to fall. When the trees are young they will initially use the water stored in the upper soil profile. This would probably cause a decrease in the throughflow component and associated saturation excess. Once established, the tree rooting systems will access the deep groundwater system and there will be a decrease in deep groundwater levels. The result will be a decrease in streamflow. However, when total vegetation cover reached its prelogging level in 1991, streamflow was less than what would had been without logging (Table 1). Similar results have been reported elsewhere in Australia and other parts of the world (Kuczera, 1987; Jayasuriya et al., 1993; Hornbeck et al., 1993). If streamflow continues to decline, trees could be thinned to increase streamflow yield if considered appropriate (Ruprecht et al., 1991; Stoneman, 1993).

5.4 Implications for March Road Catchment

Following logging, the initial (maximum) increase in streamflow was due to the immediate impact of decreased interception and transpiration, an increased recharge to the shallow groundwater system and consequently an increase in throughflow. In the following years, changes in streamflow was closely related to the changes in the size of the groundwater discharge area. This implies the deep groundwater system plays an important role in streamflow generation following logging and subsequent regeneration. In the high rainfall zone of south-west of Western Australia, groundwater level lies closer to the surface. This study suggests clearing would result in a substantial increase in streamflow. In the low rainfall zone (<900 mm) the permanent groundwater level lies well below the stream invert (Bari and Boyd, 1993). Even after total catchment clearing, the rise in groundwater level will be substantially delayed. The results from this study indicates there will be little increase in streamflow in the Low Rainfall Zone until the groundwater level rises and intersects the ground surface.

6 CONCLUSIONS

- After logging, the annual streamflow at March Road catchment increased with the reduction in interception and transpiration, decreased soil moisture deficit, increased recharge to the shallow groundwater system and an increase in throughflow. The maximum increase was 18% of rainfall in 1983, one year following logging and regeneration.

- The increase in base flow was about twice the increase in quick flow.

- As the vegetation grew, interception and transpiration increased causing a reduction in streamflow.

- Groundwater level rose in the valley and in the upslope areas until 1985 and then began to decline.

- After logging, the vegetation cover increased reaching its prelogging levels in 1991.

- The groundwater discharge area increased following logging, peaked at 8% of the catchment area in 1984 and began to contract as the vegetation grew back.

- Although the groundwater discharge area is only a small percentage of catchment area it has a major role in streamflow generation.

- The effect of clearing and regeneration on streamflow generation processes is not a simple relationship where all streamflow components increase due to the increase in available water. The contribution of each component is dependent upon the hydrology of the particular catchment, rainfall and the age of the regenerating vegetation.

7 RECOMMENDATIONS

- The current level of streamflow and salinity monitoring should be continued at March Road and April Road South catchments. However, the frequency of groundwater monitoring may be reduced as recording of annual minimum and maximum levels will be adequate.

- The collected data should be reviewed in approximately five years time.

8 ACKNOWLEDGMENTS

We are grateful to the personnel of the Water Authority of Western Australia for measuring and supplying hydrological data. We also thank to Mr P Goodman, K Baldock and Dr C Jeevaraj for their comments on this manuscript.

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