Water Authority
of Western Australia

A REVIEW OF REFORESTATION EXPERIMENTS TO CONTROL LAND AND STREAM SALINITY IN WESTERN AUSTRALIA

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Water Authority
of Western Australia

Water Resources Directorate

Surface Water Branch

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ABSTRACT

Land and stream salinity is a major environmental and economic problem in Western Australia. Replacement of deep-rooted, perennial vegetation with shallow-rooted annual crops and pasture has led to rising groundwater tables and transport of previously stored salts to streams and ground surface. Initiatives were taken to reverse the process by partial reforestation of the cleared lands. During the period of 1977 to 1983, the Water Authority established a number of experimental reforestation sites in the Darling Range of Western Australia. Different reforestation methods were trialled to determine the effects of reforestation on groundwater level, groundwater salinity, streamflow and stream salt load.

Tree establishment was generally successful in mid and upslope areas. In salt affected and water logged valleys, tree survival was generally poor.

Groundwater levels beneath reforestation declined significantly during the study period (1979-91). The rate of groundwater level reduction was proportional to the percentage of the cleared area planted, stem density and location. Reduction in groundwater levels ranged from 1 m to 6 m. It appears that after 10 years of reforestation, groundwater levels have stabilised as a result of groundwater system reaching a new recharge-discharge equilibrium. Spatial average groundwater salinity declined beneath both reforestation and pasture, with pasture showing the greatest reduction. Measurement of soil salinity under native forest remained practically unchanged, declined considerably beneath reforestation and pasture at midslopes and increased in the unsaturated zone on the valley floor.

Due to reforestation, streamflow declined depending upon the percentage of cleared area planted. It appears low density plantings of less than 18% of the highly salt affected cleared area has little effect on streamflow. The effects of reforestation on stream salinity and salt load were not significant at two of the highly salt affected and water logged

catchments. This was due to low success rate of reforestation in the valleys. It is expected that with time additional salts accumulated in the valley will be leached out and reforestation will result in a reduction in stream salt discharge. However, there was a continuous and systematic reduction in stream salt load from a catchment where 76% of the cleared area was planted at a high tree density. At this site the highest annual streamflow reduction was 68 mm with a corresponding annual yield of 15 mm (rainfall 865 mm).

Since 1970s, the annual rainfall has been 5 to 10% lower than the long term average. If the long term average rainfall conditions prevailed, it is likely that the reduction in streamflow and groundwater level would have been less. But it is not clear how it would have affected stream salt load.

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1 INTRODUCTION

Land and stream salinity is a major environmental and resource problem in the south-west of Western Australia. Since European settlement, more than 443000 ha of cleared land has become salinised (George, 1990). The area of salt affected land is increasing. Most of the rivers and wetlands in the agricultural areas have already been salt affected. It is anticipated that salinity will continue to increase for at least another 50 years in the region where annual rainfall is below 900 mm (Schofield and Ruprecht, 1989)

Increasing land and stream salinity in the south-west of Western Australia is a by-product of agricultural development (Ruprecht and Schofield, 1991; Schofield and Ruprecht, 1989; Schofield et al., 1988; Williamson et al., 1987; Wood, 1924). Replacement of deep-rooted (>20 m, Dell et al., 1983), perennial, native forest with shallow-rooted annual agricultural crops and pastures has disturbed the hydrological balance. Groundwater levels had risen as a result of a reduction in evapotranspiration and increasing groundwater recharge (Schofield et al., 1988). Rising groundwater has dissolved salts previously "stored" in the unsaturated zone and discharged them to the land surface and/or streams (Williamson, 1986).

One approach to reclaim the salinised lands and streams is to reforest cleared lands. Partial reforestation was considered most promising. Reforesting only a part of the catchment was determined to be sufficient for evaporation to exceed annual rainfall thereby controlling the rising groundwater levels and hence land and stream salinity.

In 1970s, the State Government passed legislation to control large scale agricultural development of marginal (salinity 500-1500 mgL^{-1}, Total Soluble Salts, TSS) water resource catchments (Mundaring, Wellington, Warren, Kent and Denmark) in the south-west of Western Australia (Fig. 1). At that time it was recognised stream and land salinity may increase further due to past clearing, and that active rehabilitation was necessary in the Low Rainfall Zone (<900 $mmyr^{-1}$) of the catchments. A significant proportion of this rainfall zone had been cleared for agriculture and large quantities of salt exist in the landscape (Stokes et al., 1980). In the 1970s and early 1980s, perennial, deep-rooted trees were planted in the Low Rainfall Zone areas with the purpose of reversing the rising trend in groundwater level and salinity. Trees were mainly planted on the lower slopes adjacent to the streams in an effort to minimise groundwater salt discharge to the streams.

In the 1970s, a number of experimental sites were established with various reforestation methods in the south-west of Western Australia (Fig. 1). The primary aim of these experiments was to understand the effects of reforestation on land and stream salinity. The specific objectives were to:

(i) assess the effects of reforestation on groundwater level and salinity;

(ii) determine the effects of reforestation on streamflow;

(iii) quantify the changes in stream salinity and stream salt load following reforestation.

Results from these study sites had previously been reported (Bari and Schofield, 1992; Bari and Boyd, 1992; Bari 1992a, b, c; Schofield and Bari, 1991; Schofield et al., 1991; Bari et al., 1990; Bell et al., 1990). This report reviews all the results and presents the current knowledge and understanding of the hydrological processes related to reforestation in the south-west of Western Australia.

2 SITE DESCRIPTION

2.1 *Location*

The experimental sites are located in the Low Rainfall Zone of south-west Western Australia (Fig. 1). This area of the state has a mediterranean climate with cool, wet winters and dry, hot summers. The long term average annual rainfall (1926-76) ranges from 625 mm to 880 mm (Hayes and Garnut, 1981) and the annual pan evaporation ranges from 1300 mm to 1600 mm (Luke et al., 1988). About 80% of rainfall occurs in the winter months (May to October). Details of the experimental sites are given in Table1.

The surface soils (<1 m) of the region are highly permeable and the rainfall intensity rarely exceeds the infiltration capacity (Sharma et al., 1987). The subsurface clay soil (>1 m) has low permeability and often forms a perching layer. The soil profiles are lateritic. The depth of weathering ranges from zero (rock outcrop) to more than 20 m. A 0.2 m to 0.8 m thick layer of aluminosillicates, known as hard pan, exists on the valley floor at most of the sites. The average depth of groundwater level across the sites ranges from 1 m to 7 m. Except at the Padbury Road site, the average groundwater salinity was more than 4000 mgL^{-1} Total Soluble Salts (TSS) (Table 1). Groundwater salinity varied considerably across all sites. Groundwater discharge areas were evident at Maringee Farm, Batalling Creek and Padbury Road catchments.

The native forests within the study areas are dominated by jarrah (Eucalyptus marginata), marri (E. calophylla) and wandoo (E. wandoo). The cleared areas had been under clover-based pasture for at least 20 years prior to reforestation.

2.2 *Instrumentation and Measurement*

Daily rainfalls were recorded by pluviometers installed at each site. For the periods of

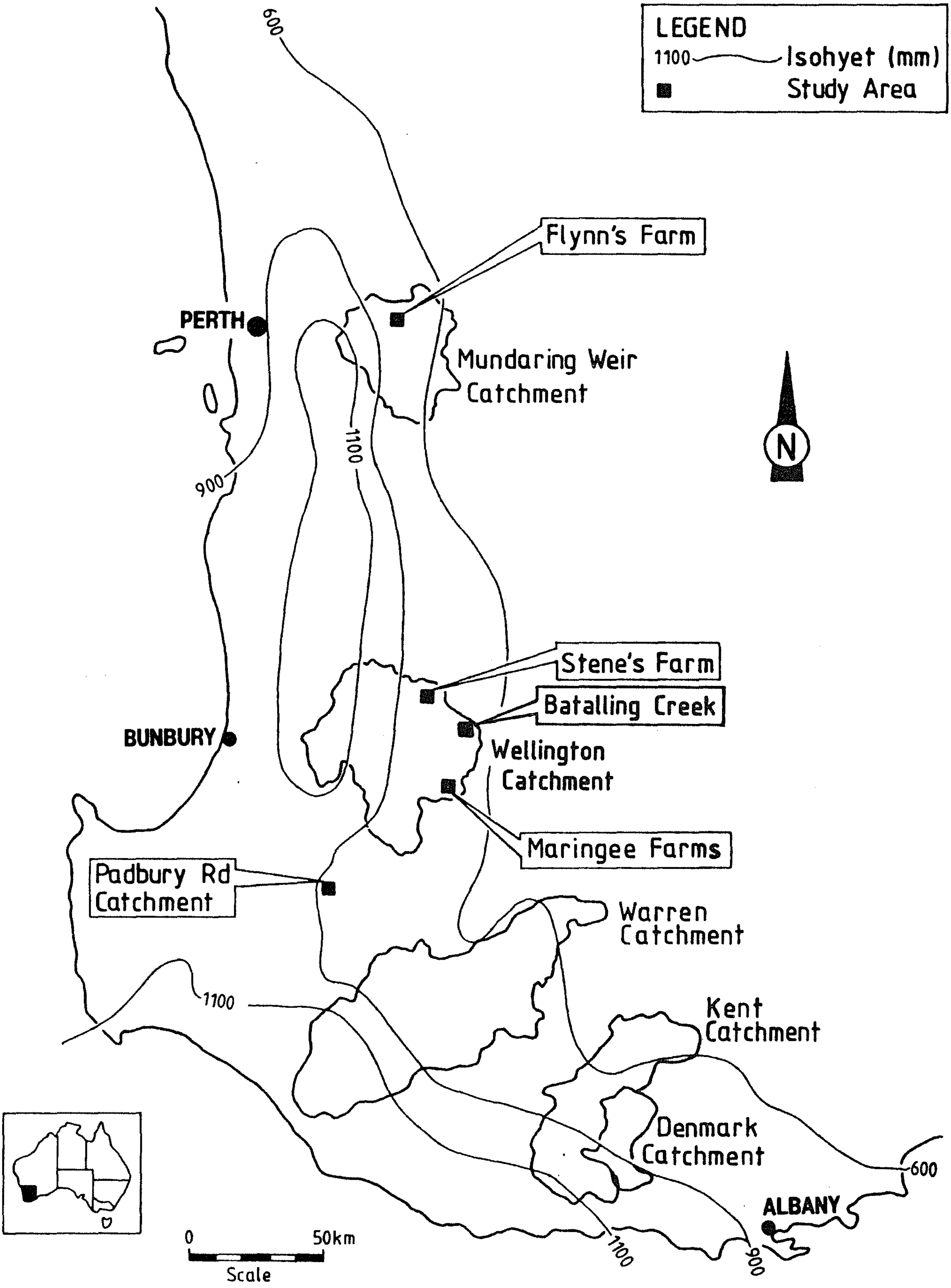

Figure 1. Location of the study areas.

Table 1: Characteristics of the experimental sites

Site	Annual rainfall (mm)	Planting year	Species planted	Initial stem density (sph)	Stem density (sph)		Site cleared (%)	Cleared area planted (%)	Crown cover (%)		Initial depth to water table (m)	Initial groundwater salinity (mg/L TSS)	
					1986	1993			1987	1993		Mean	Range
Flynn's Agroforestry	725	1978	P. radiata P. pinaster E. camaldulensis	380 to 1140	75 to 225	75 to 225	51	58	14	33	4.4	2800	190-7950
Flynn's Landscape	725	1977	E. camaldulensis E. wandoo	670	500	425	98	8	43	59	2.1	4600	330-16000
Flynn's Hillslope	725	1978/79	E. camaldulensis E. wandoo	1200	1000	480	100	54	29	36	1.0	7400	2400-12100
Stene's Agroforestry	725	1981/82	E. camaldulensis E. sargentii E. wandoo	1250	150 to 900	150 to 630	25	57	25	25	2.7	6550	430-11600
Stene's Strip planting	725	1976/77	E. globulus E. camaldulensis P. pinaster	1200	600	420	31	14	47	37	2.7	7700	150-24600
Stene's Valley planting	725	1979	E. wandoo E. rudis E. camaldulensis	625	500	450	44	35	41	41	6.3	5760	2590-9370
Stene's Arboretum	725	1979	63 eucalypt and 2 pine species	625	0 to 600	0 to 600	35	70	39	49	7.1	5060	360-12670
Maringee Farm	640	1981/82	E. camaldulensis E. wandoo	625	250	150	54	18	-	20	2.2	15600	370-22800
Batalling Creek	640	1985/87	E. camaldulensis E. cornuta E. wandoo	830	-	310	51	38	-	31	2.0	12000	260-19700
Padbury Road	880	1977/83	P. radiata E. globulus	625 to 1100	650	650	64	74	-	-	4.0	2000	150-4000

missing records (<1% of total records), rainfall data were interpolated from the nearest pluviometer using a correlation between two stations.

A network of groundwater observation bores were installed at each experimental site. Groundwater levels were measured approximately once a month. Salinity was measured from samples collected within the screen area of the bores.

A sharp-crested V-notch weir was installed at each of Maringee Farm, Batalling Creek and Padbury Road catchments to measure stream discharge. Stream salinity samples were obtained using an automatic pumping sampler and were routinely analysed for electrical conductivity. Electrical conductivity of stream water has been recorded continuously since the installation of the weirs. A few selected samples were analysed for major ions from which a relationship between stream salinity (Total Soluble Salts, TSS) and electrical conductivity (mS m^{-1}) was derived. The flow-weighted mean daily stream salinity (or simply stream salinity, S) was computed as:

$$S=(\Sigma S_i Q_i)/\Sigma Q_i$$

where Q_i and S_i are the streamflow and salinity at 15 minute interval. Annual stream salinity was calculated in the same way from the daily stream salinity and flow.

2.3 *Experimental Method*

In Western Australia, the principal method used by the Water Authority to control land and stream salinity has been tree planting on the lower slopes and groundwater discharge areas. This method was considered most appropriate because partial reforestation was expected to lower groundwater level in the valley and eliminate groundwater salt discharge into the stream. It was also argued that lower slope and discharge zone planting would have a direct and quicker effect on reducing stream salinity (Loh, 1985). Therefore, during the period of 1977-83, a number of experimental sites were established to evaluate the ability of reforestation to lower groundwater levels and stream salinity (Table 1). Four reforestation methods were tested in the south-west of Western Australia.

These methods were: (a) agroforestry, (b) lower slope and discharge zone planting, (c) strips or small blocks strategically placed on the site covering small proportion of the cleared area, (d) extensive, dense planting covering high proportion (>50%) of the cleared area. Reforestation details of the experimental sites are given in Table 1.

3 PLANTATION ESTABLISHMENT AND MANAGEMENT

Trees were planted at the experimental sites between 1977 and 1983. The predominant species planted were eucalypts and pines (Table 1). The area planted varied from 8% to 74% of the cleared area. Trees were planted at the reforestation sites with a wide range of initial stem densities, ranging from 380 to 1200 stems per hectare (sph). Crown cover (the percentage of the ground area covered by the vertical projection of the vegetation canopy) was measured by a crownometer similar to the one described by Montana and Ezcurra (1980).

3.1 Agroforestry

Agroforestry is the technique of planting trees in widely spaced rows over a large proportion of the cleared area which enables agriculture to occur between the rows of trees. This method was tested at two sites: Flynn's and Stene's agroforestry (Fig. 1). At Flynn's site, pines and eucalypts were planted in 1978 at stem densities ranging from 380 to 1140 sph. At Stene's site, 3 species of eucalypts were planted in 1981 at a stem density of 1250 sph (Table 1). Trees were thinned and pruned periodically until 1986 (Table 1). At Flynn's agroforestry, crown cover increased considerably during 1986-91 while it remained stable at Stene's site (Table 1).

3.2 Landscape and Strip Planting

Landscape and strip planting represent high density, low percentage of cleared area planting placed strategically over the landscape. Flynn's landscape and Stene's strip planting are example of this technique (Table 1). At Flynn's site, 8% of the cleared area was planted at a stem density of 670 sph. Tree establishment was very successful at this site. By 1993, tree density had been reduced to 425 sph while the average crown cover across the site had increased to 59% (Table 1). At Stene's strip planting, tree density had reduced from 1200 sph to 420 sph as a result of natural attrition. Average crown cover had reduced from 47% to 37% (Table 1).

3.3 Lower slope and Discharge Zone Planting

Another type of reforestation trialled was high density tree planting of 20-50% of the cleared land in the lower slope and discharge areas of the site. This technique was used at Stene's valley planting, Maringee Farm and Batalling Creek (Fig. 1). Trees were planted at stem densities ranging from 625 to 830 sph (Table 1). At Maringee Farm and Batalling Creek, tree establishment was not successful in groundwater discharge areas along the stream. On some plots, only the more vigorous species planted in every fifth row survived. In 1993, tree density were measured in the range of 150 sph to 450 sph and the crown cover varied between 20% and 59%. Trees were not thinned or pruned at these study sites.

3.4 Extensive Planting

High density reforestation by extensively planting more than 50% of the cleared area has been investigated at three sites: Flynn's hill slope, Stene's arboretum and Padbury Road. The initial tree density ranged from 625 sph to 1200 sph. However, tree density has reduced over time at all sites (Table 1). At Flynn's hill slope and Stene's arboretum, average crown cover increased considerably during the study period. The pine trees planted at Padbury Road were thinned during the study period.

4 RESULTS

4.1 Annual Rainfall

The average annual rainfall at the experimental sites during the study period was 5% to 10% less than the long term average recorded from 1926 to 1976. Only in 1981 and 1988, was annual rainfall considerably higher than the long term average (Fig. 2 and Fig. 3).

4.2 Groundwater Level

4.2.1 Agroforestry

The effects of agroforestry plantations on groundwater levels have been investigated at two sites, Flynn's and Stene's agroforestry. The average groundwater level changes beneath agroforestry compared to pasture is shown in Fig. 2 and Fig. 3. At both sites reforestation has resulted in a reduction in groundwater levels relative to pasture and ground surface. However, the reduction in groundwater level relative to pasture has halted in recent years. This suggests a new recharge-discharge equilibrium has been reached.

4.2.2 Landscape and strip planting

The landscape and strip planting method involves planting of trees in strips or blocks covering only a small percentage (<15%) of the cleared area. This method is being tested in two sites: Flynn's landscape and Stene's strip planting sites (Fig. 1). Relative to the pasture control, there has been no significant decline in groundwater level at Flynn's landscape (Fig. 2) while at Stene's strip planting there has been a decline of 1 m (Fig. 3)

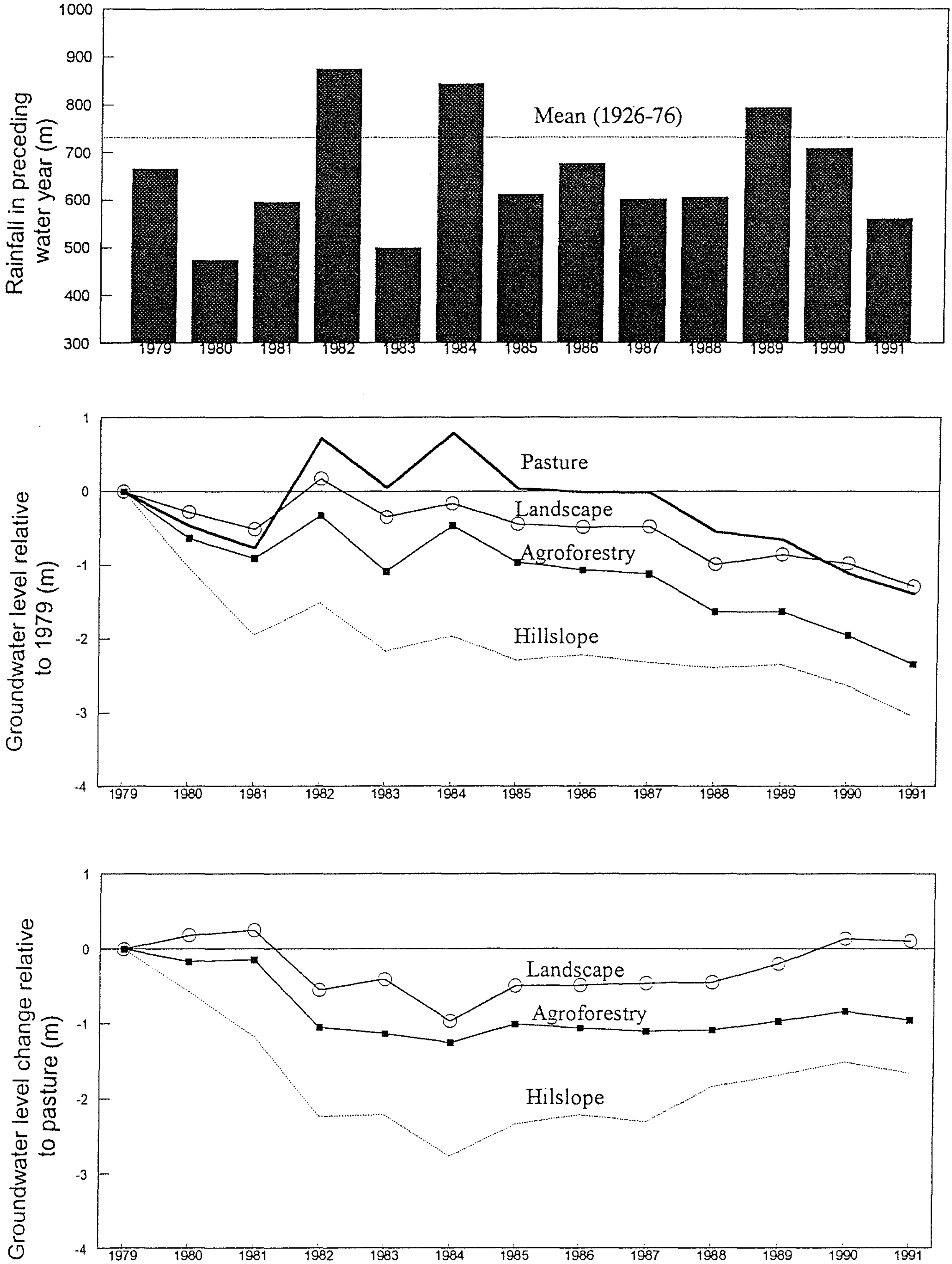

Fig. 2 Annual rainfall and groundwater response at Flynn's farm

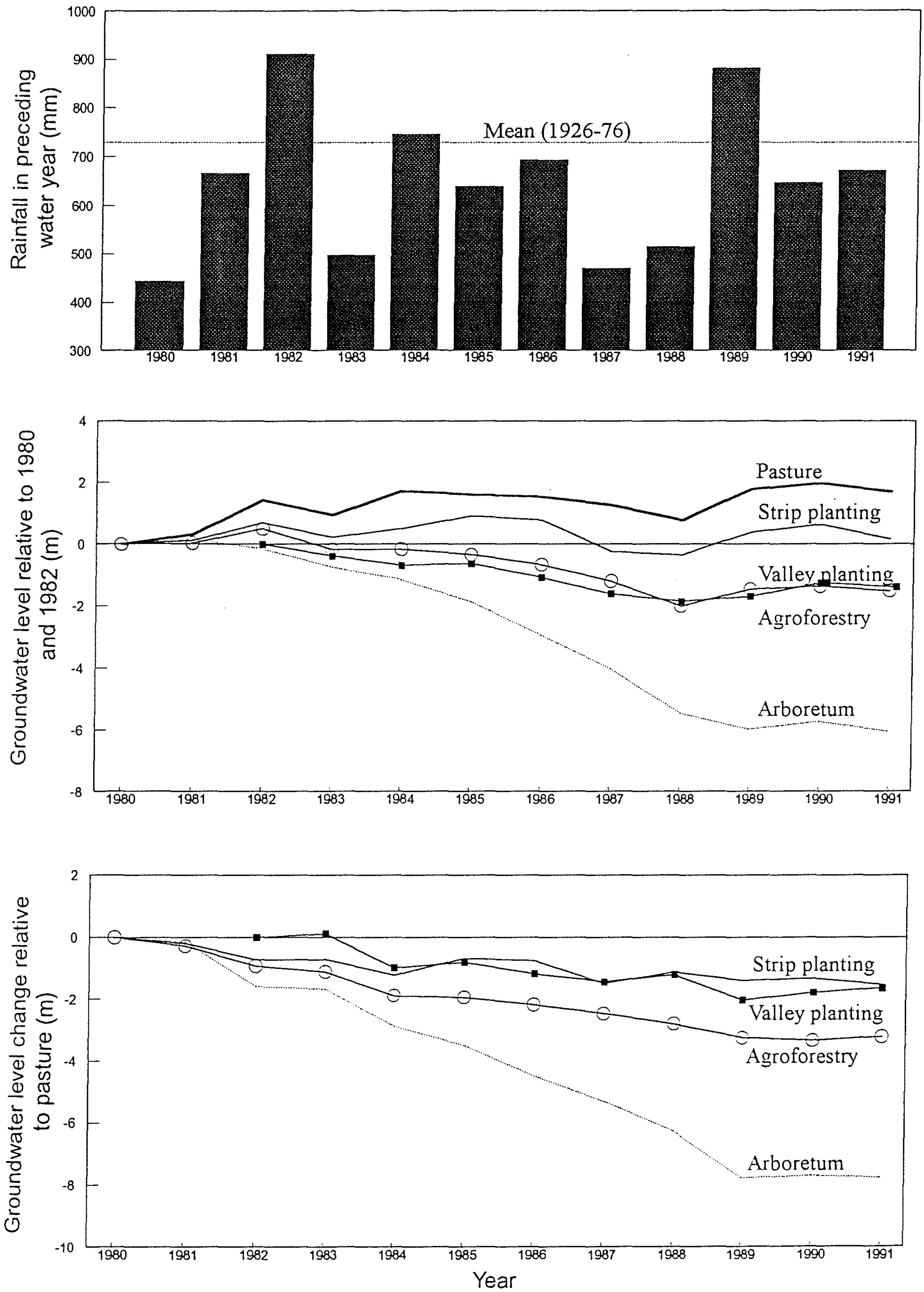

Fig. 3 Annual rainfall and groundwater response at Stene's farm

4.2.3 Lower slope and discharge zone planting

This method has been tested at three sites: Stene's valley planting, Maringee Farm and Batalling Creek. Only the Stene's valley planting site has enough data for analysis. During the period of 1982-91, groundwater beneath reforestation at Stene's valley planting declined by 2 m relative to pasture control (Fig. 3). A comparison of groundwater level through the valley cross-section is shown in Fig. 4. The groundwater level has remained stable beneath native forest, increased under the pasture and declined beneath reforestation. This is a good example of localised impact of reforestation on groundwater levels.

4.2.4 Extensive planting

This method has been investigated in three sites: Flynn's hill slope, Stene's arboretum and Padbury Road catchment. At Padbury Road there is not enough groundwater data for analysis. During the period of 1979-91, groundwater level beneath Flynn's hill slope declined 2 m relative to pasture control (Fig. 2). Stene's arboretum had the highest decline in groundwater levels. Beneath reforestation groundwater level declined by 6 m while under pasture it rose by 2 m (Fig. 3). However, the reduction in groundwater level varied across the site. The highest reduction was on the valley floor (6 m) and the lowest being at upper midslopes (4 m) (Fig. 5).

4.3 Groundwater and Soil Salinity

4.3.1 Groundwater salinity

Groundwater salinity changes were derived by comparing data collected in 1989, following bore pumping, to data collected at the onset of reforestation. There were considerable changes in groundwater salinity over time among individual bores at all sites. Average groundwater salinity has declined at all sites except Flynn's landscape (Table 2). The maximum reduction was at Flynn's pasture, 33%, while the minimum reduction was at Stene's strip planting, 1%. At Flynn's landscape, the average

Table 2: Changes in groundwater salinity at the experimental sites

Site		Groundwater salinity (mg/L TSS)		% Change
		Onset of reforestation	1990	
Flynn's	Pasture	3690	2480	-33
	Agroforestry	2810	2510	-11
	Landscape	6880	7220	+5
	Hillslope	8340	6920	-17
Stene's	Pasture	2410	1430	-41
	Agroforestry	6500	6140	-6
	Strip planting	7560	7470	-1
	Valley planting	5660	3950	-30
	Arboretum	5010	4460	-11
Maringee Farm	Pasture	13160	11140	-16
	Reforestation	18160	17680	-3

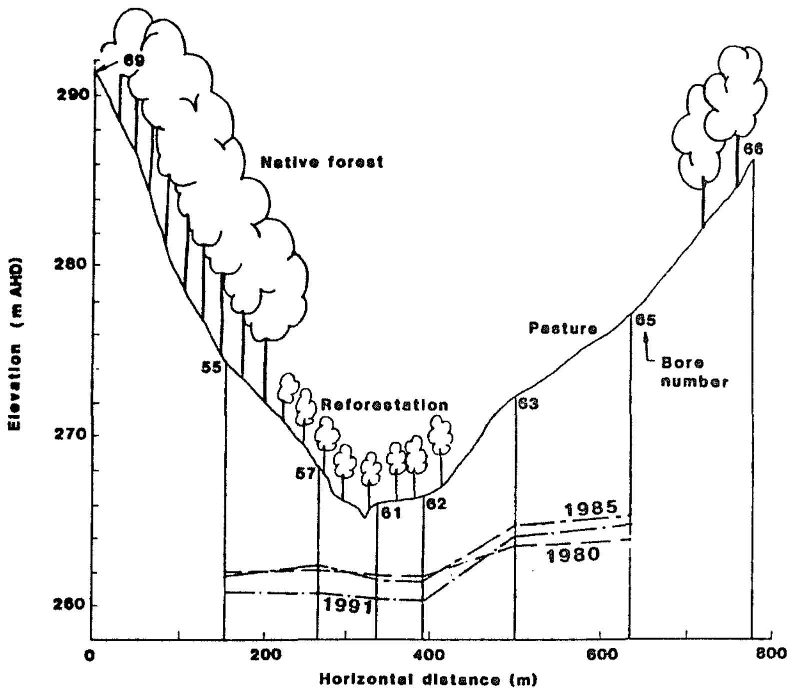

Fig. 4 Groundwater level across the valley at Stene's valley planting site

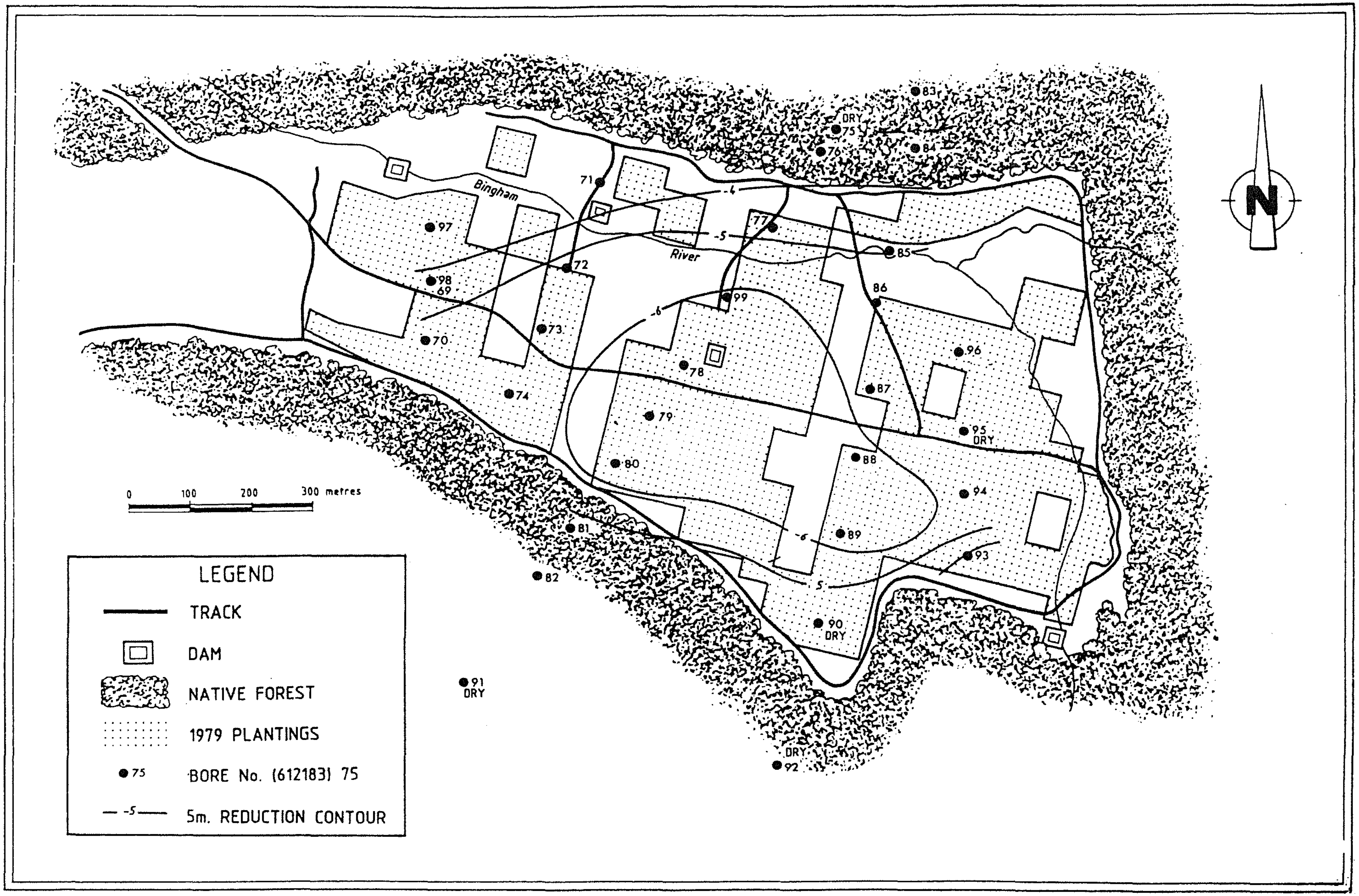

Figure 5 Contours of the reduction of ground water level at Stene's arboretum site.

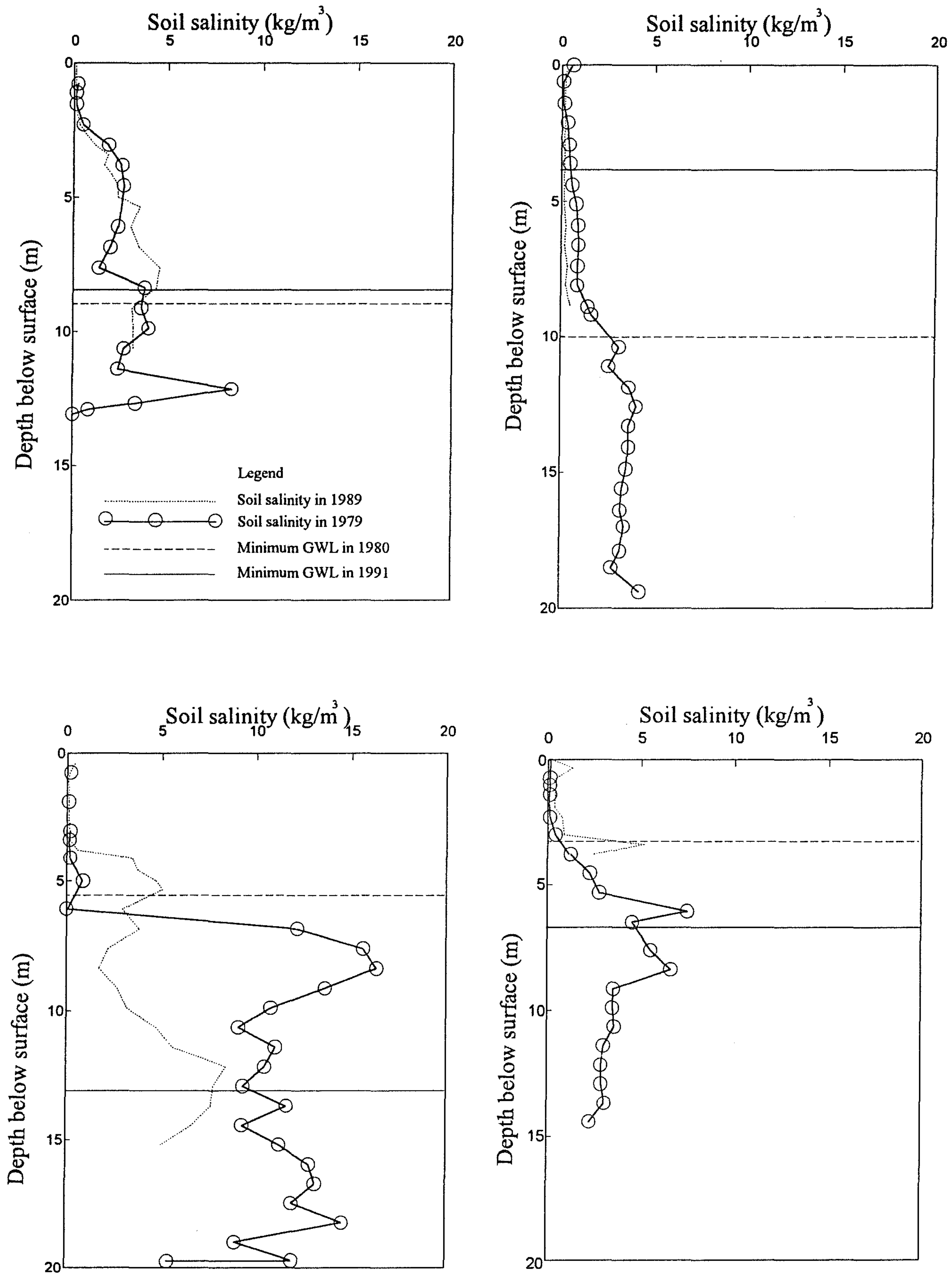

Fig. 6 Soil salt profiles beneath (a) native forest, (b) pasture, (c) reforestation and (d) valley

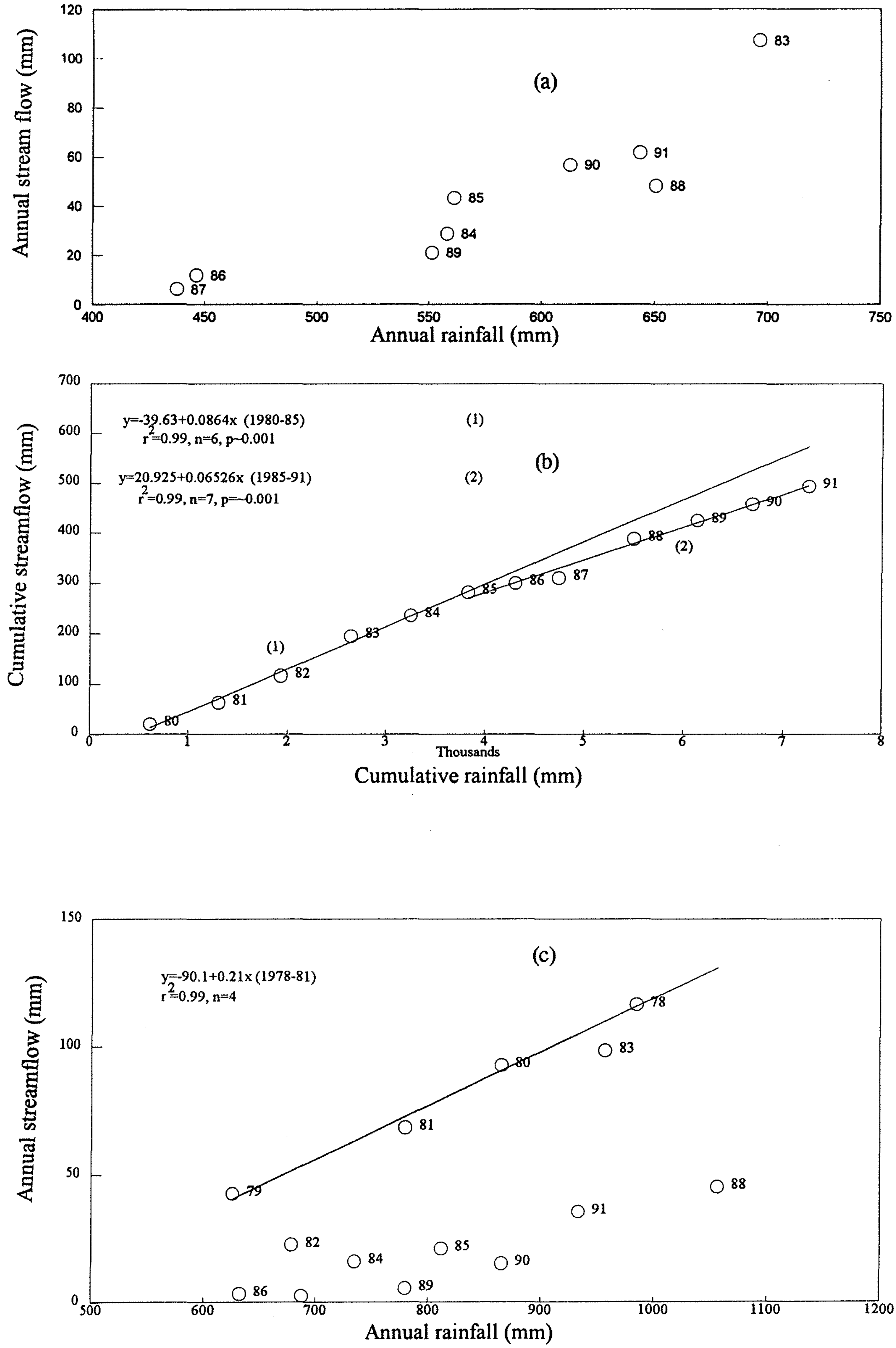

Fig. 7 Annual streamflow and rainfall at (a) Maringee Farm, (b) Batalling Creek and (c) Padbury Road catchments

groundwater salinity increased by 5% (Table 2).

4.3.2 Soil salinity

The salt content in the soil profile at each experimental site was measured at the onset of reforestation and in 1989. Typical changes in soil salinity profiles over time are shown in Fig. 6. Soil salinity in the unsaturated zone beneath native forest remained unchanged (Fig. 6a) while beneath pasture it declined (Fig. 6b). Under reforestation at midslope, soil salinity decreased in the unsaturated zone (Fig. 6c). However, it increased in the valley where seasonal groundwater discharge areas were evident (Fig. 6d).

4.4 Streamflow and Stream Salinity

There has been continuous monitoring of streamflow and stream salinity at three experimental reforestation sites: Maringee Farm, Batalling Creek and Padbury Road. Data from these catchments were analysed in detail and reported by Bari (1992b, c) and Bari and Boyd (1992).

4.4.1 Effects of reforestation on streamflow

The effects of reforestation on streamflow was assessed by evaluating the relationship between annual streamflow and rainfall during the study period. There was no pretreatment data for Maringee Farm and Padbury Road. However, it was assumed that reforestation would have had negligible effects on the catchment water balance in its first four years' of growth. Therefore, the first four years' data were considered as pretreatment data for these two catchments. The regression equations for the streamflow and rainfall during the "pretreatment" period were developed for the Maringee Farm, Batalling Creek and Padbury Road. Based on the regression equations annual streamflows were estimated as if the sites had remained cleared. The difference between the observed and the estimated streamflows was considered to be the effects of treatment.

For Maringee Farm catchment, the effects of reforestation on streamflow were not obvious (Fig. 7a). It appears, if a catchment like this is highly salt affected, where tree survival was low (<150 sph), planting 18% of the cleared area has little effect on streamflow, at least in first 7 years of reforestation.

The relationship between annual cumulative rainfall and streamflow at Batalling Creek is shown in Fig. 7b. After reforestation in 1985, streamflow declined at an average rate of 12 mm yr^{-1} (~2% of annual rainfall) due to the higher evapotranspiration of the plantings. This equated to a reduction in streamflow of 30% compared to what would been expected if the site had not been reforested.

There has been a fundamental change in streamflow volumes at Padbury Road since reforestation (Fig. 7c). During the period 1982-91, streamflow declined an average of 60 $mmyr^{-1}$. After 1983, streamflow reduction was more systematic (Fig. 8a). The maximum reduction in annual streamflow occurred in 1990 and was about 8% of rainfall. The average reduction in streamflow since reforestation was about 67% of the streamflow expected had this site remained cleared.

4.4.2 Effects on stream salinity and salt load

The changes in stream salinity and salt load due to reforestation was calculated from the relationship between the streamflow, stream salinity and salt load. In the south-west of Western Australia, the relationship between streamflow, stream salinity and salt load are highly non-linear (Loh and Stokes, 1981). Stream salinity decreases as flow increases while salt load increases with an increase in streamflow. Therefore, the changes in stream salinity due to reforestation was not the difference between the observed salinity and the salinity predicted by the "pretreatment" regression equations. In fact, it is the difference between the observed salinity and the salinity predicted by the regression equation for the streamflow that would have occurred had this site remained cleared. For example, at Padbury Road the observed streamflow and salinity in 1984 were 16 mm and 1725 mgL^{-1} TSS respectively. If there had been no reforestation in 1984, the streamflow and stream salinity would had been 63.4 mm (from the pretreatment relationship between streamflow and rainfall) and 1140 mgL^{-1} TSS (from the pretreatment relationship between streamflow

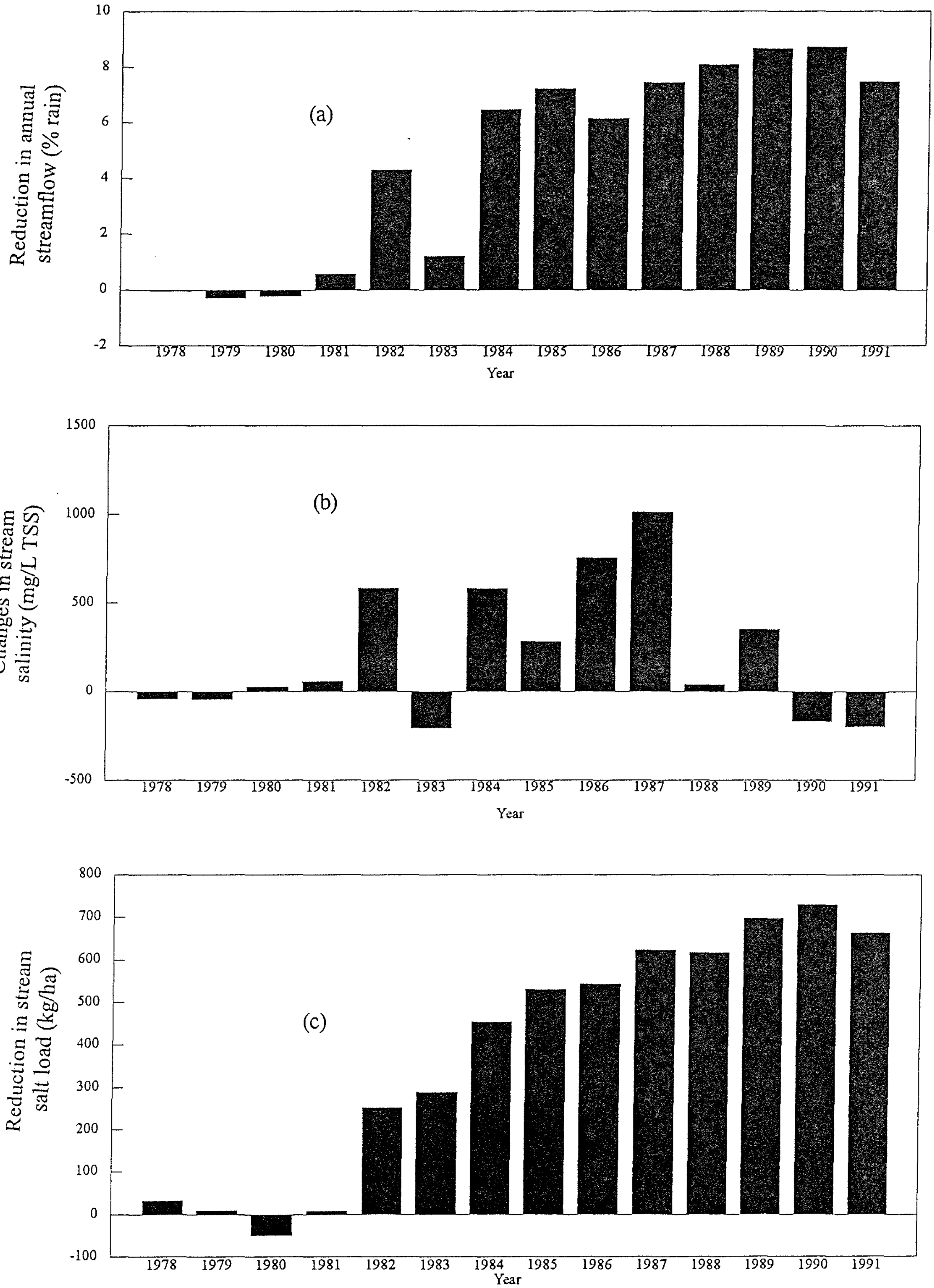

Fig. 8 Changes in (a) streamflow, (b) stream salinity and (c) stream salt load at Padbury Road catchment

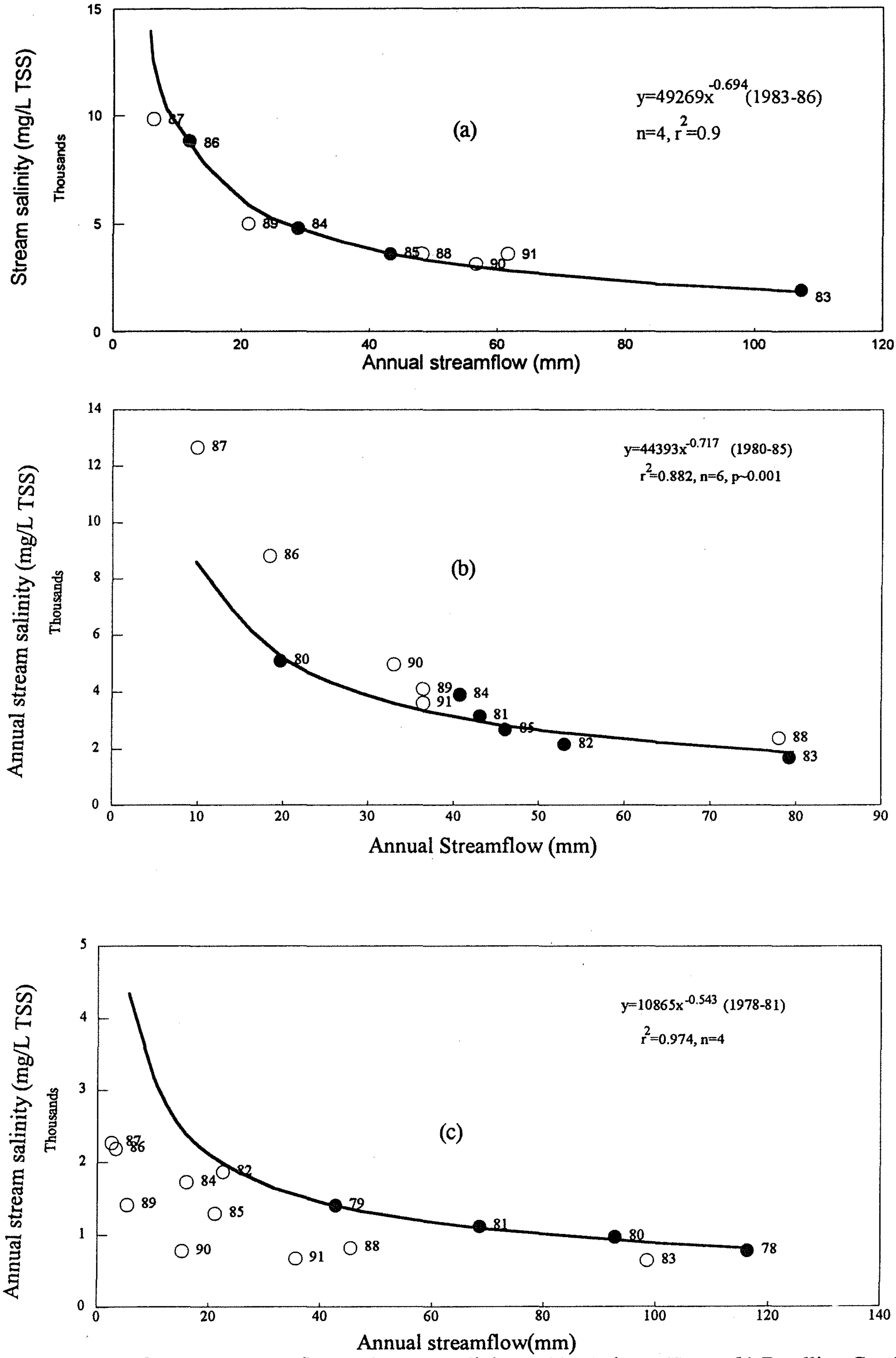

Fig. 9 Annual streamflow and stream salinity at (a) Maringee Farm, (b) Batalling Creek and (c) Padbury Road catchments

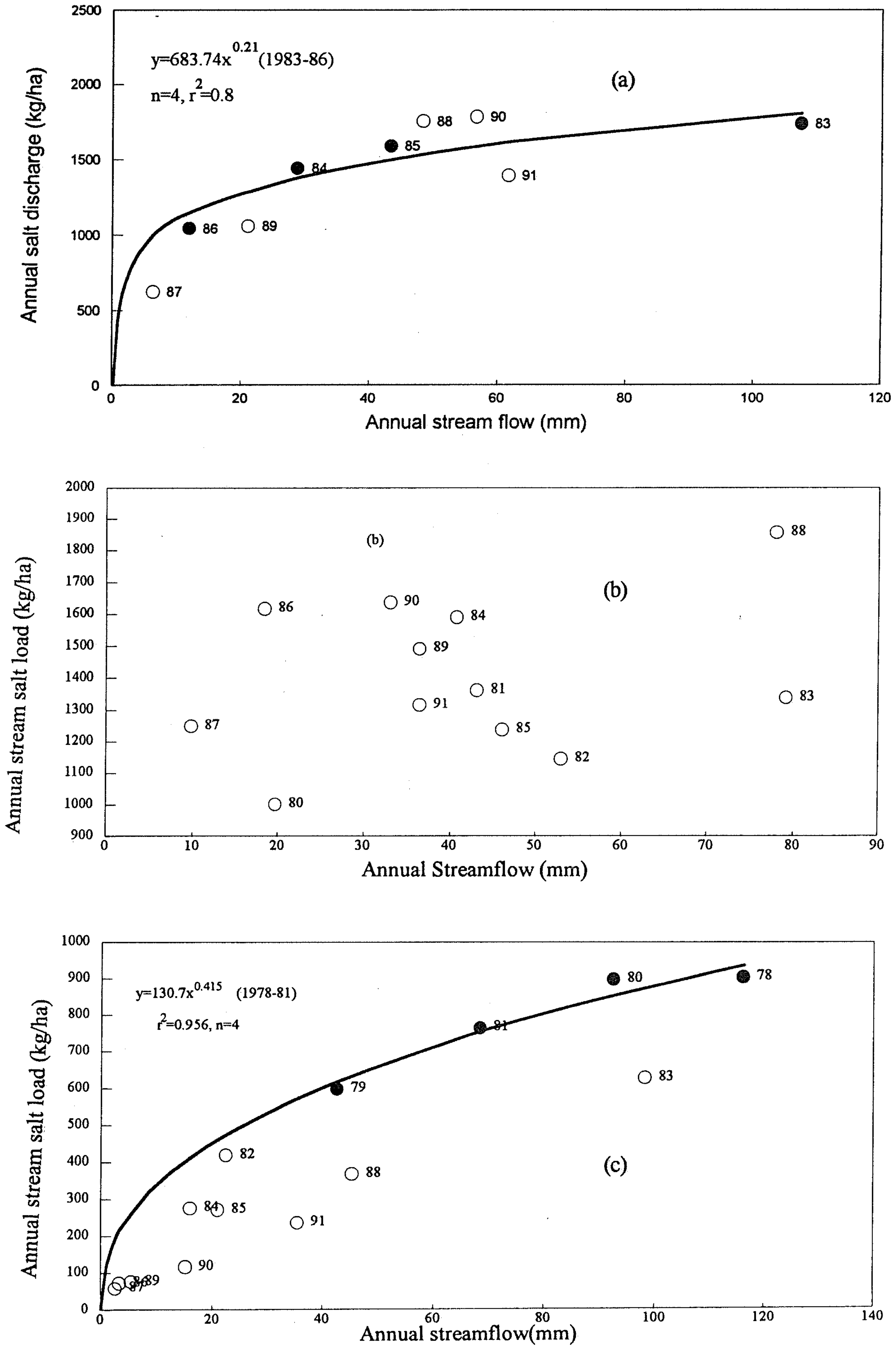

Fig. 10 Annual streamflow and stream salt load at (a) Maringee Farm, (b) Batalling Creek and (c) Padbury Road catchments

and salinity). Therefore, the increase in stream salinity due to reforestation was 585 mgL^{-1} TSS. The method for calculating stream salt load change was similar.

At Maringee Farm and Batalling Creek, there were no significant changes in stream salinity following reforestation (Fig. 9). Stream salinity increased following reforestation at Padbury Road (Fig. 8b). After 1983, stream salinity increased significantly. The highest salinity increase of 1000 mgL^{-1} TSS was observed in the low rainfall year of 1987. However, since 1987 there had been a trend of decreasing stream salinity. In 1991, stream salinity was about 200 mgL^{-1} TSS lower than what would have been expected if the site remained cleared.

The effects of reforestation on stream salt load were not obvious at Maringee Farm and Batalling Creek (Fig. 10a, b). However, at Padbury Road, stream salt load decreased substantially following reforestation (Fig. 10c). Since 1983, the reduction in stream salt load has been systematic and continuous. The maximum reduction of 730 $kgha^{-1}$ TSS occurred in 1990 (Fig. 8c).

The groundwater discharge areas were measured from aerial photographs taken at the onset of reforestation and in 1990. The groundwater discharge area had not changed at Batalling Creek and had reduced at Maringee Farm and Padbury Road.

5 DISCUSSION

5.1 Annual Rainfall

During the study period (1979-91), the average annual rainfall at the experimental sites was 5 to 10% lower than the long term average (1926-76). The lower-than-average rainfall conditions have assisted in lowering groundwater levels and reducing streamflow. However, if long term average rainfall conditions had prevailed, it is likely the reduction in groundwater level and salinity would had been less. However, it is not clear how it would have affected stream salinity.

5.2 Vegetation Establishment

Salt affected and water logged areas exist along the stream lines at most of the experimental sites. Tree establishment was poor in these areas. However, improved reforestation techniques are being developed to establish trees on salt affected and water logged areas (Pettit and Froend, 1992). These techniques include: (a) ripping of a cemented layer of aluminosilicate (hard pans) which exist in the valley at most of the sites; (b) double ridge mounding and (c) increasing size of seedling container; (d) improved species selection and stock control. These techniques have already resulted in greater survival and growth of trees.

5.3 Groundwater Level

Groundwater levels declined beneath reforestation at all study sites. The reduction varied from one site to the other, depending upon the percentage of cleared area planted, stem density and vegetation cover. The lowest reduction in groundwater level was at Flynn's landscape site, where only 8% of the cleared area was planted (Fig. 2). The maximum reduction was at Stene's arboretum, where 70% of the cleared area was planted at a high stem density (Fig. 3 and Fig. 5). However, since 1988 the reduction in groundwater level relative to pasture has slowed down (Fig. 2 and Fig. 3). It seems that after 10 years of reforestation, the groundwater systems achieve a new equilibrium. Reduction in relative groundwater level has stopped beneath reforestation at Flynn's landscape (Fig. 2). This implies planting less than 10% of the cleared area is not sufficient to significantly lower and sustain groundwater levels on lower and midslopes. On the other hand, extensive dense planting over a large proportion of the cleared area is the best method when rapid and large reductions in groundwater levels are required. However, this method has limited application due to its competition with agriculture.

5.4 Groundwater and Soil Salinity

The decline in groundwater salinity beneath reforestation was less than beneath pasture. Except Flynn's landscape planting, groundwater salinity declined under reforestation at all sites (Table 2). This may mean that the solute leaching from the groundwater system beneath the reforestation is occurring at a faster rate than increasing concentration due to increased evapotranspiration of groundwater. Another possibility is that salts are accumulating in the unsaturated zone in the valley as groundwater levels fall (Fig. 6d). There was a substantial decline in groundwater salinity and soil salinity situated beneath the midslope reforestation and pasture (Fig. 6c). This indicates lateral leaching of soil salts. The salinity profiles beneath native forest remained practically unchanged due to negligible groundwater recharge.

Groundwater salinity beneath reforestation at Flynn's landscape planting increased (Table 2) while there had been no significant changes in groundwater level (Fig. 2). A substantial decline in groundwater salinity was observed beneath pasture (Table 2). The pasture bores are located on the upslope of the reforestation (Bari et al, 1990). This implies a lateral leaching of soil salts from midslope and accumulation in the valley.

The groundwater discharge area did not increase during the study period. Hookey (1987), using a two-dimensional finite difference model, predicted that if there had been no reforestation, the groundwater discharge area would double by 1990. This implies that reforestation may have stopped the expansion of groundwater discharge areas.

5.5 Streamflow and Stream Salinity

The hydrological processes evident in the Darling Range of the south-west of Western Australia consist of an overland flow system, a shallow seasonal groundwater system and a deep, permanent, very saline groundwater system (Stokes and Loh, 1982; Stokes, 1985). In a typical forested catchment in this region, most of the streamflow is generated as subsurface throughflow from highly permeable surface soils and very little from deep groundwater (Stokes and Loh, 1982; Bari, 1992b). Following agricultural clearing, groundwater levels rise and ultimately reach the stream. The groundwater discharge area expands on the valley and results in a greater surface runoff and streamflow (Ruprecht and Schofield, 1989). Groundwater discharges enormous amount of salt to the stream and therefore stream salinity invariably increase (Schofield, 1988).

At Maringee Farm, Batalling Creek and Padbury Road, groundwater levels rose as a consequence of agricultural clearing and intersected the stream. Groundwater discharge areas were formed where the deep groundwater system discharges large amount of salts throughout the year. Streamflows do not occur in the dry months because the potential evapotranspiration exceeds the discharge from the deep groundwater system. A huge amount of salt is accumulated on or near the groundwater discharge area along the stream lines due to evaporation and transpiration of groundwater during summer months. This process is typical of many cleared catchments in the south-west of Western Australia.

5.6 Effects of Reforestation on Streamflow

Groundwater level decline observed beneath reforestation ranged from 1.0 m to 6.0 m. The reduction in groundwater level was dependant upon the percentage of cleared area planted, stem density and crown cover. This indicates an increase in evapotranspiration since reforestation. But the increase in evapotranspiration was not sufficient to lower streamflow at Maringee Farm (55% cleared of which 18% was planted) in the first 7 years of reforestation. However, at Batalling Creek (51% cleared of which 38% was reforested) streamflow declined at an average rate of 12 $mmyr^{-1}$ (Fig. 7b) although the salt load remained unchanged (Bari, 1992b). The effects of reforestation on stream salt load at Maringee Farm and Batalling Creek was not obvious (Fig. 10). There are three possible explanations: (a) reforestation was not very successful in the salt affected and water logged valley areas, (b) the valley areas of these two catchments comprise hard pans which may have prevented root access to deep groundwater and (c) higher groundwater salinity ($\sim$15000 mgL^{-1} TSS) at which water extraction by eucalypts species may be limited.

The effects of reforestation on salt discharge may also be influenced by the location of the plantation. At Maringee Farm and Batalling Creek, most of the valley floor and lower slope areas were planted to stop saline groundwater discharge to the stream. At Padbury Road, most of the upslope areas were planted to reduce groundwater recharge. Planting of trees at already saline groundwater discharge area is economically attractive but this method does not stop recharge in the upslope areas. On the other hand, recharge zone planting is not attractive to the farmers and it is still not proven to be effective in reducing groundwater discharge areas. However, if more areas were planted to control groundwater recharge and discharge, it is likely that reforestation would have resulted in greater reduction in stream salt load.

5.7 Reforestation for Salinity Control

Reforestation can reduce groundwater levels and streamflow. But the reductions depend upon the proportion of the cleared area planted, stem density and also the location. In general, the more trees the greater the reduction in groundwater levels and streamflow. However, the integration of appropriate levels of reforestation with other land management techniques such as remnant vegetation protection, higher water using agricultural systems is necessary to gain optimum results.

Reforestation resulted in a substantial reduction in stream salt load at Padbury Road, but this was due to flow volume reduction rather than reduction of saline seepage in the valley floor. At highly salt affected Maringee Farm and Batalling Creek the effects of reforestation on salt load was not obvious in first 7 years of reforestation. This may imply that many years of leaching of additional salts accumulated in the valley has to occur before there can be a reduction in stream salt load.

In the 1970s clearing controls were put in place and reforestation was undertaken in the highly-valued marginal (salinity 500 to 1500 mgL^{-1} TSS) water resources catchments in the south-west of Western Australia. These catchments were Mundaring, Wellington, Warren, Kent and Denmark (Fig. 1). In Wellington Dam catchment, more than 50% of salt and less than 10% of inflow to the reservoir originates from the region with less than 700 mm annual rainfall (Loh, 1988). In the 1980s, more than 6500 ha of cleared land was planted and another 2500 ha are being planted. The main objective was to decrease groundwater level and thereby control and reduce stream salt discharge to the reservoir (Loh, 1988; Schofield et al 1989; Bari, 1992b). Results from these experimental sites in the Wellington Dam catchment suggest, if tree establishment in the valley floor and lower slopes is successful in covering more than 20% of the cleared area, reforestation will control and eventually reduce salt flow to the reservoir.

6 CONCLUSIONS

6.1 Reforestation

Tree establishment was successful in mid and upslope areas. In the salt affected and water logged valley floor, tree survival was poor.

6.2 Groundwater Level and Salinity

Reforestation can reduce saline groundwater levels. The rate of groundwater level reduction was proportional to the percent of cleared area planted, stem density and location.

After 10 years of reforestation, the reduction in groundwater level slowed down and was stabilised as the groundwater system reached a new recharge-discharge equilibrium.

Groundwater salinity beneath reforestation declined at all sites except at Flynn's landscape. The increase in groundwater salinity at Flynn's landscape was attributed to a lower percentage (<8%) of cleared area being planted and the positioning of the plantation in the valley floor. The reduction in groundwater salinity beneath pasture on the midslopes, was generally higher than beneath reforestation.

The soil salinity profiles under native forest remained practically unchanged; declined considerably beneath reforestation and pasture at mid slopes and increased in the unsaturated zone in the valleys.

6.3 Streamflow and Salinity

Following reforestation, streamflow declined at Batalling Creek and Padbury Road. At

Maringee Farm, the effects of reforestation was not obvious. This may be because the low percentage (~ 18%) of the clear area planted, low stem density and severe salt and water logging in the valley.

The effects of reforestation on stream salinity and salt load were not significant at Maringee Farm and Batalling Creek. This was due to the low success rate of reforestation in the salt affected and water logged valleys. However, it is expected that with time additional salts accumulated on the valley will be leached out and reforestation will result in a reduction in stream salt discharge.

At Padbury Road, there has been a continuous and systematic reduction in stream salt load. The highest reduction was about 730 kg ha^{-1} TSS in 1990. However, there was no corresponding reduction in stream salinity until 1987 because most of the salt load reduction was due to a decline in total flow. Since 1987 there are indications that annual stream salinity is now reducing in response to reforestation.

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