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Groundwater Level and Salinity Response Beneath Valley Reforestation at Stene's Farm in the Darling Range of Western Australia

by M. A. Bari, N. J. Schofield and D. W. Boyd

Report No. WS 73

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SUMMARY

Stream and groundwater salinities have increased in the south-west of Western Australia due to the replacement of deep-rooted, native, perennial vegetation with shallow-rooted annual agricultural crops and pastures. The process involved a decrease in evapotranspiration leading to a rise in groundwater tables accompanied by the dissolution and transport of salts to the streams. Research began in 1970s to reverse the process by lowering the groundwater table with partial reforestation of the cleared land.

One important partial reforestation strategy is high density plantation of the valley floor covering typically 20%-50% of the cleared land. This strategy, termed valley planting, has been carried out operationally in the eastern Wellington Dam catchment covering some 6000 ha to 1990. This report describes the groundwater level and groundwater salinity response to a valley plantation at Stene's Farm (~700 mm yr^{-1} rainfall) in the Darling Range of Western Australia. The groundwater level and salinity data are analysed for the period 1980 to 1989.

During the study period (1980-89), the minimum groundwater level beneath the valley planting site declined 3.25 m compared to the pasture control and 2.65 m compared to the native forest. The reduction relative to the ground surface was 1.47 m. The rate of reduction was fairly uniform which is attributable to the continuous crown growth of the plantations. The maximum groundwater level dropped 3.2 m relative to pasture, 2.61 m relative to the native forest and 1.2 m relative to ground level.

The annual changes in minimum groundwater level were compared with the annual rainfall of the preceding year. The results implied if the annual rainfall was less than 605 mm over the pasture site, the minimum groundwater level would decline in the following year. Similarly, the minimum groundwater level would decrease beneath valley planting if the preceding year's rainfall

was less than 700 mm. During 1980-89 annual rainfall was 8% lower than long term average. The results indicated minimum groundwater level would have risen under pasture and would have fallen under valley planting if long term average rainfall conditions had occurred.

Groundwater salinity beneath valley reforestation reduced by 30% during the study period. Under pasture the reduction in groundwater salinity was greater (41%) and under native forest the reduction was lower (13%). The trend of declining water table and decreasing groundwater salinity should reduce stream salinity with time.

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1. INTRODUCTION

Stream salinisation as a result of agricultural development has been recognised as a major problem in the south-west of Western Australia (Schofield et al., 1988; Schofield and Ruprecht, 1989). Prior to the agricultural development, all divertible surface water resources were believed to be fresh. It is generally accepted that the replacement of native deep-rooted vegetation to shallow-rooted crops and pasture increased the stream salinity.

Research began in 1970s to rehabilitate the salt-affected catchments. Partial reforestation of the cleared land was found to be most promising. During the late 1970s, a number of experimental sites were established with various reforestation strategies embracing different layouts and densities of trees. One of them was the Stene's Farm valley planting site where the valley floor and lower slopes were planted at a high density. This strategy is partly discharge control and partly recharge control and aims to lower the groundwater table in the vicinity of the streamline and so prevents groundwater solute discharge to streams. This strategy has been carried out operationally on the Wellington Dam catchment since 1979, with planting covering 6000 ha of farmland to date (Schofield et al., 1989).

The Stene's Farm valley planting is located in the Wellington Dam catchment. The plantation, consisted of five species of Eucalyptus established in fourteen blocks of variable size. The reforestation covered 35% of the farmland. This report presents the most in-depth and up-to-date analysis of the data from this site and is an important contribution to the assessment of valley planting reforestation strategy to salinity control. Earlier, less detailed hydrological analyses of the data of this site were reported by Anderson et al., 1982; Edgeloe et al., 1984; Bell et al., 1988; and Schofield et al., 1989. The results are compared to an agroforestry site also established at Stene's Farm (Bari et al., 1991).

2. SITE DESCRIPTION

2.1 Location

The experimental site is located in the Darling Range, approximately 40 km North of Collie (Fig. 1). It lies within the predominantly forested Wellington Dam catchment.

2.2 Site History and Layout

The experimental site consists of two parts : the valley planting site and control site (Fig. 1). Both sites comprise part farmland (pasture), native forest and reforestation. Clearing of the native forest for pasture development took place during the 1950s. In 1976 the site was purchased by the State Government as part of a programme to reforest farmland within Wellington Dam catchment and to control the inflow salinity to Wellington reservoir.

The valley planting site has a catchment area of 127 ha and is more or less elliptical in shape (Fig. 2). The Bingham River flows through the middle of the catchment. During 1980-89 the annual mean flow-weighted salinity ranged from 258 mg L^{-1} TSS to 1496 mg L^{-1} TSS. Clearing took place on the lower slopes of the site covering 44% of the catchment. The plantation was established in 1979 covering 35% of the cleared area. At that time average depth to minimum and maximum groundwater levels was 6.3 m and 2.8 m respectively. The average groundwater salinity was 5400 mg L^{-1} TSS. Saline seeps were evident on the upper valley reaches of the catchment.

The control site lies 1 km east of the valley planting site (Fig. 1). About 31% of the total area was cleared leaving very little native vegetation near the river. Between 1976 and 1978, strip reforestation was carried out on the lower slopes covering about 14% of the cleared area. The groundwater control bores were

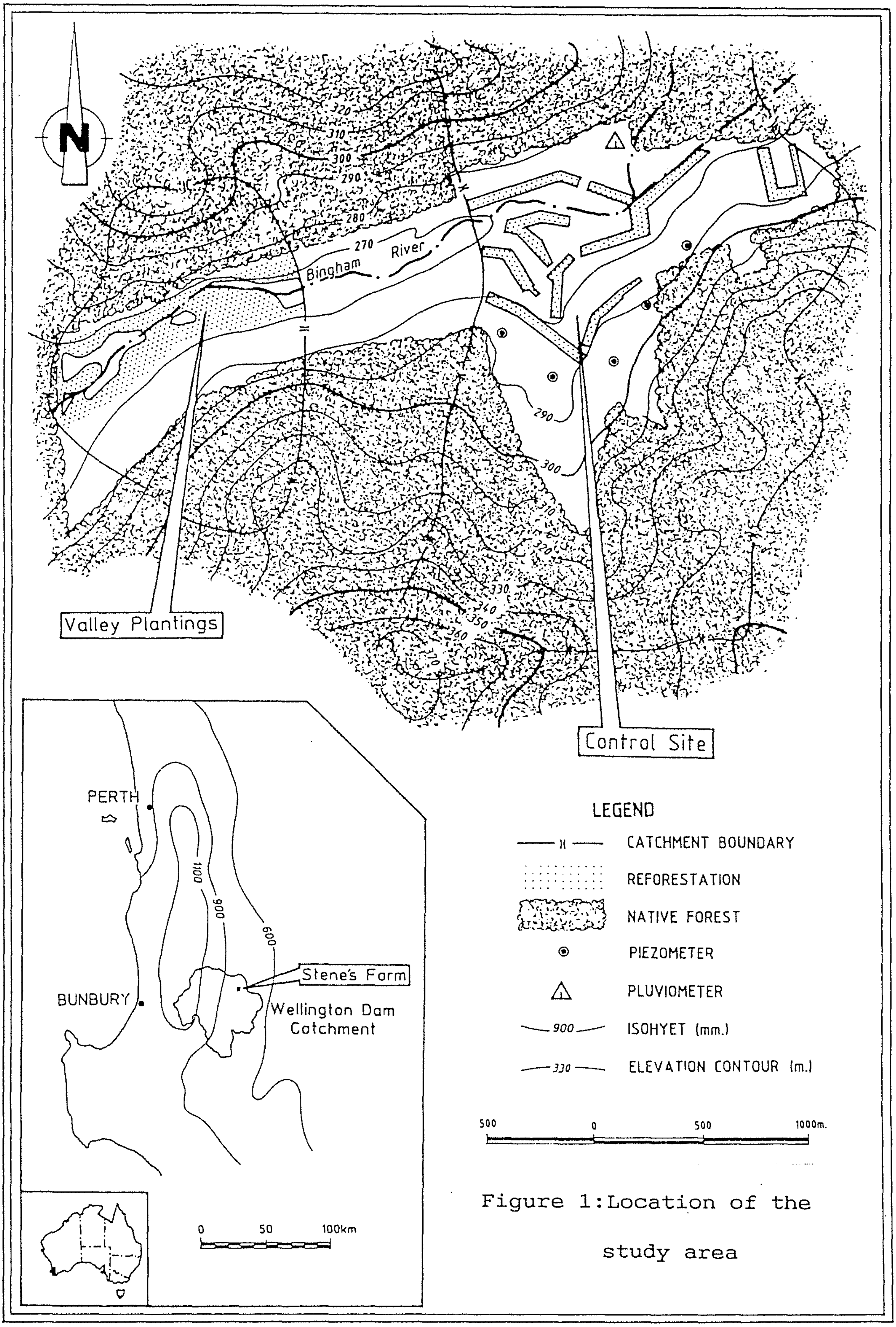


Figure 1: Location of the study area

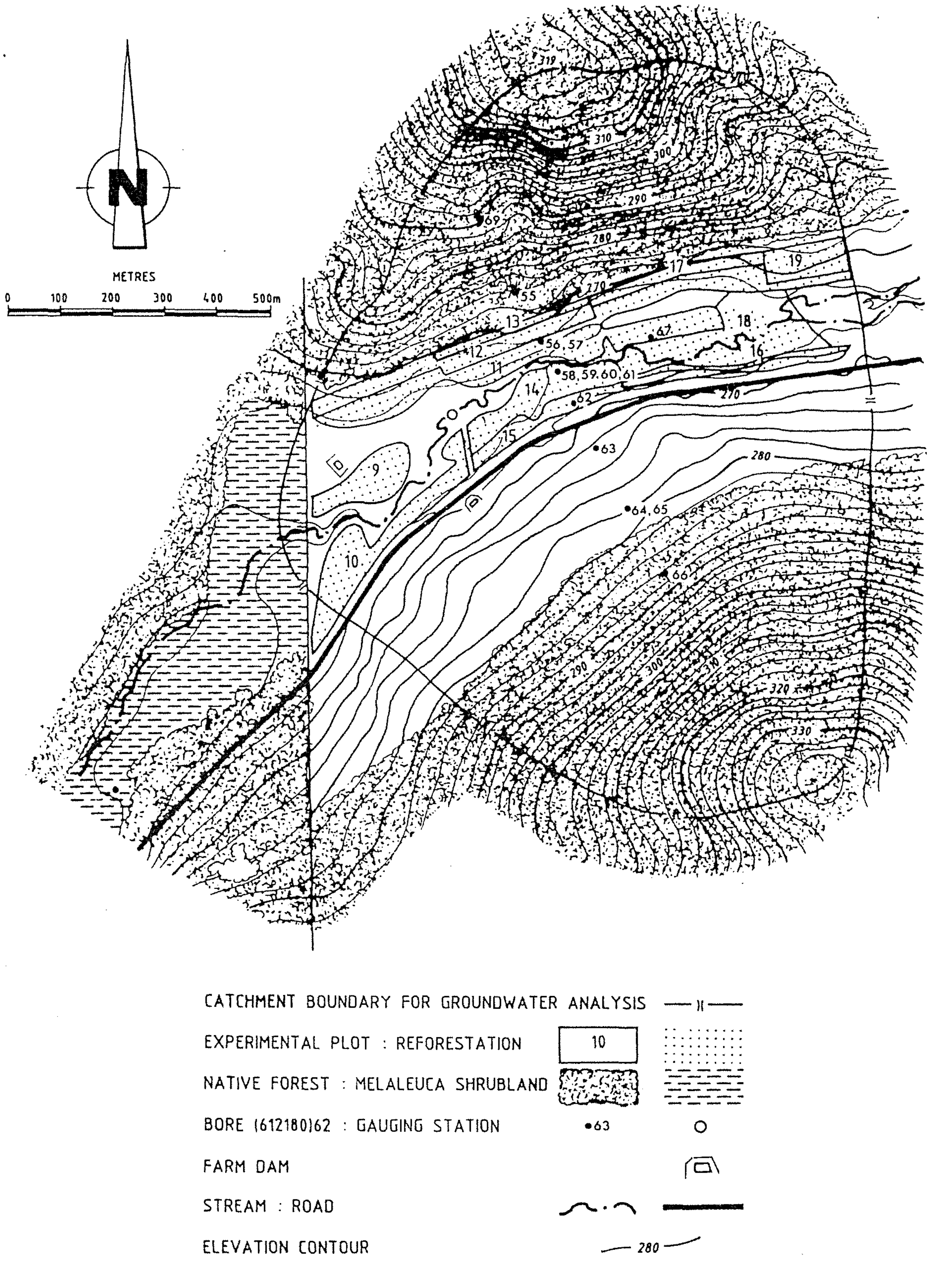


Figure 2:Reforestation layout and hydrometric network

drilled on the middle slopes, between the reforestation and the native forest.

2.3 Climate

The Wellington catchment area has a Mediterranean climate with cool, humid, wet winters and hot, dry summers. About 80% of the total annual rainfall occurs in winter. The long term average rainfall (1926 to 1988) of the experimental site is 713 mm yr^{-1}. The annual average pan evaporation of the catchment is 1600 mm (Luke et al., 1988). Temperatures range from a maximum in excess of 40°C, which could be expected to occur in January to February, to a minimum of less than 0°C occurring in June or July.

2.4 Topography

The elevation of the valley planting site is shown in Fig. 2. The upslope forested portion of the catchment is slightly steeper than the reforested zone. Most of the bores are located in the reforested portion where ground slope averages 3%.

The elevation of the control site varies from 271 m AHD to 374 m AHD. The mean slope of the catchment is 3.8%, which is comparable to the valley planting site.

2.5 Soil and Geology

The surface soils of both sites are highly permeable and the rainfall intensity rarely exceeds the infiltration capacity of the soil (Sharma et al., 1987; Ruprecht and Schofield, 1989). Soil profiles are generally lateritic and of granitic origin. The profile mainly consists of shallow silty sands with some clay gravels of variable thickness overlying a sandy clay subsoil. The depth of weathering is more than 20 m. The geological cross-section of the valley is shown in Fig. 3.

The soil and geology of the control site is similar to that of the valley planting site. Sand and sandy clays are common near the soil surface, while the subsoil has a variable sandy clay matrix. The depth of weathering of this site is also more than 20 m.

2.6 Vegetation

In the past the cleared area of the site had germination of annual rye, barley and other grasses. Five species of Eucalyptus were planted in 1978 (Table 1), details of which are given in section 4. The upslope native vegetation is dominated by jarrah (E. marginata) with the principal sub-dominants being marri (E. calophylla) and wandoo (E. wandoo).

On the lower slope of the control site there is reforestation covering about 14% of the cleared area, comprising two species of pinus and eleven species of Eucalyptus planted during 1976-78 in strips while the remainder was left under pasture (Fig. 1).

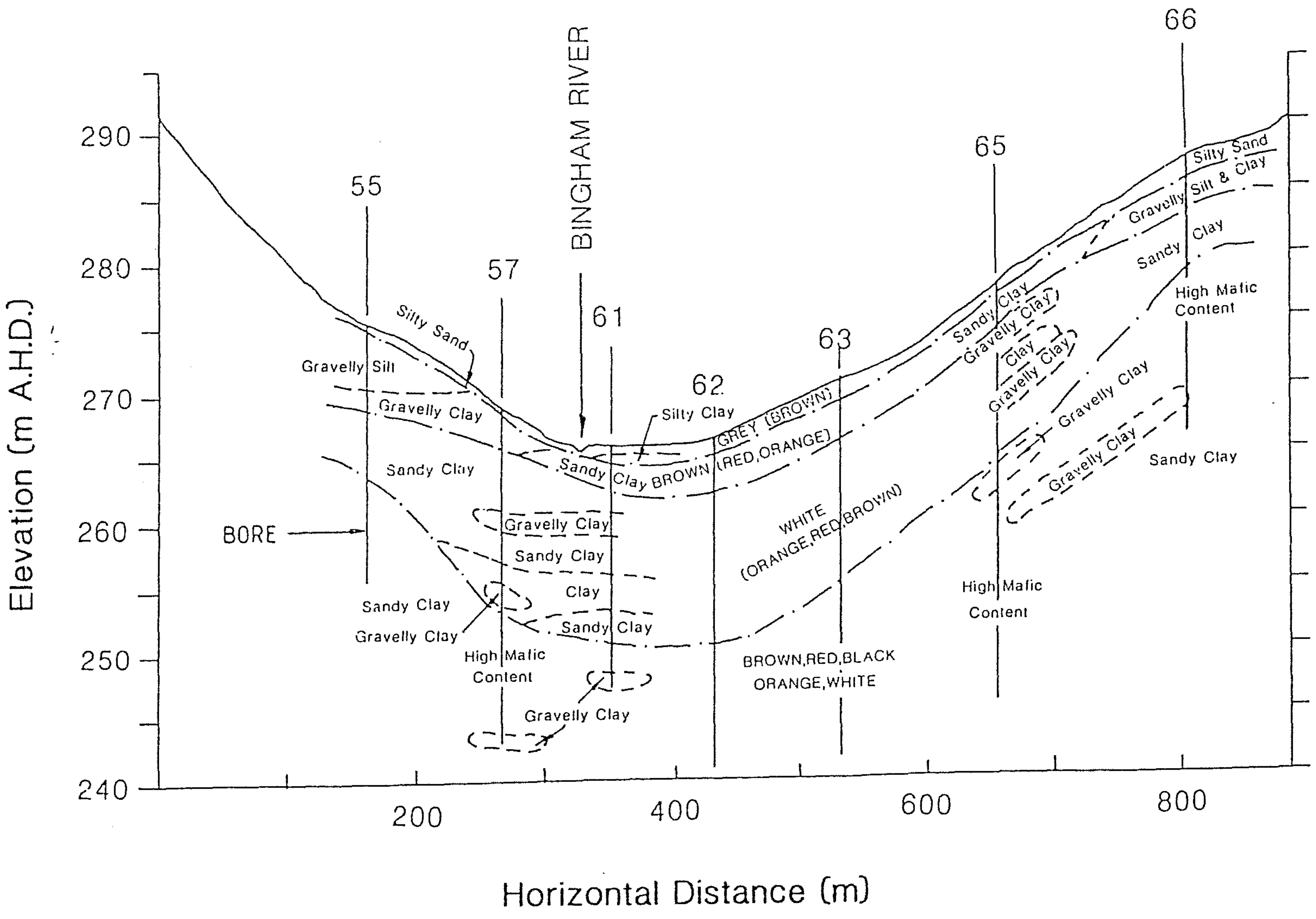


Figure 3:Geological cross-section of the experimental site

Table 1 : Hydrogeological and plantation details of the experimental site

Plot No	Hydrogeological				Reforestation				Crown Cover (%)
	Area (ha)	SWRIS bore no.	Initial depth to watertable (m)	Initial mean salinity (mg L^{-1})	Species planted	Year planted	Stem density (stems/ha) 1979	1988	
9	1.0	-	-	-	E. rudis	1979	625	550	
10	2.2	-	-	-	E. camaldulensis	1979	625	550	
11	5.4	61218067	1.95	4420	E. rudis	1979	625	500	41
12	2.0	61218056-57	5.6	4377	E. wandoo E. globulus	1979	625	500	43
13	0.5	-	-	-	E. calophylla E. globulus	1979	625	350	
14	1.7	61218058-61	4.10	4823	E. rudis	1979	625	550	33
15	1.8	61218062	5.11	9183	E. wandoo	1979	625	450	47
16	0.5	-	-	-	E. camaldulensis	1979	625	350	
17	0.7	-	-	-	E. wandoo E. globulus	1979	625	450	
18	2.7	-	-	-	E. rudis		625	150	
19	1.0	-	-	-	various Eucalyptus				

3. EXPERIMENTAL OBJECTIVES

3.1 Plantation

The main objective of the reforestation strategy was to lower the groundwater levels significantly in a relatively short period of time (~ 10 years).

3.2 Hydrology and Salinity

The objectives of the groundwater monitoring programme were to:

(i) identify the initial groundwater table conditions prior to reforestation treatment;

(ii) determine seasonal variations and longer term trends of groundwater table beneath pasture and native forest;

(iii) determine the effect of valley planting on groundwater level;

(iv) identify the groundwater flow direction and any change due to the reforestation treatment;

(v) determine spatial and temporal variability in groundwater salinity and the effect of valley planting on groundwater salinity; and

(vi) determine changes in solute distribution through the soil profile in response to reforestation.

4. PLANTATION ESTABLISHMENT, MANAGEMENT AND GROWTH PERFORMANCE

4.1 Plantation Establishment and Layout

In 1979 a 200 m wide strip of trees were established across the valley on both sides of the river. Further upslope, a 200 m wide and 1100 m long strip was left under pasture for existing sheep grazing. The valley planting site consists of eleven blocks of variable size (Fig. 2). The area of each block is given in Table 1. Most of the observation bores were drilled along a valley transect which cuts across the plantation, pasture and native forest areas.

4.2 Plantation Management

There was no thinning or pruning at the study site. But due to natural death, tree density changed in latter years. The present stem density varies from 150 sph (stems per hectare) to 550 sph. The density on most blocks is over 350 sph (Table 1).

4.3 Crown Cover

Crown cover is defined as the percentage of the ground area covered by the vertical projection of the vegetation canopy on the ground surface. Measurements of crown cover of the trees at the valley planting site were taken on the 9th of December, 1987 using a crownometer similar to the one described by Montana and Ezcurra (1980). Crown cover of the valley planting site varies from 33% to 47% with an average of 41% (Table 1).

5. HYDROLOGICAL DATA COLLECTION

5.1 Rainfall

Rainfall records were taken from the pluviometer M509374 located approximately 1.5 km east of the catchment boundary (Fig. 1). For periods of missing rainfall records, data from the nearest pluviometer (M509337) were transposed using the correlation developed by Bari et al., 1991. Rainfall record was missing for only 4.5% of the time from pluviometer M509374. The long term average rainfall (1926-86) for this study site had previously been estimated as 722 mm yr^{-1} (Hayes and Garnaut, 1981; Bell et al., 1990). The long term average rainfall extended to 1988 by including the pluviometer data, is 713 mm yr^{-1}.

5.2 Groundwater Monitoring

The groundwater bore networks for the control and valley planting sites are shown in Fig. 1 and Fig. 2 respectively. The pasture control bores are located at the upper mid-slope of the control site (Fig. 1). These bores are drilled to bedrock and completed with slotted lengths varying from 6 m to 18 m (Table 2a).

Twenty bores were drilled at the valley planting site. Some of the bores were beneath the native forest, outside the catchment boundary. The groundwater bore network within the valley planting site consisted of one bore transect and one additional bore in the valley floor reforestation area. At two locations on the bore transect, nests of bores were installed to determine vertical pressure head distribution (Fig. 2). Table 2b details all bores at the valley planting site.

Monitoring of the groundwater bores commenced in 1979. Piezometric level and salinity were measured approximately once a month. Salinity (Total Soluble Salts, TSS) of collected samples was determined by using the relationship between the TSS (mg L^{-1})

and electrical conductivity (mS m^{-1}) developed by Bari *et al.*, 1991.

Table 2a : Details of observation bores - control site

S.W.R.I.S. Bore Number	Drillers Bore Number	Commencement of Operation	Bore Classification	Top of Inner Tube (AHD)	Natural Surface Level (AHD)	Bottom of Tube (AHD)	Length of Slotting (m)	Length of Inner Tube (m)	Height of T.O.I.T. Above N.S.L. (m)	Depth of B.O.T. Below N.S.L. (m)
61218008	8-76	01/06/1976	Pasture	295.767	295.090	274.677	18.00	21.09	0.677	20.413
61218009	9-76	01/06/1976	Pasture	291.092	290.400	274.432	14.00	16.66	0.692	15.968
61218038	22-77	30/07/1977	Pasture	284.607	284.020	266.22	6.00	18.39	0.587	17.80
61218044	29-77	30/07/1977	Pasture	287.460	286.860	271.36	8.50	16.10	0.600	15.50
61218045	30-77	30/07/1977	Pasture	285.512	284.880	267.38	11.00	18.13	0.632	17.50

Table 2b : Details of observation bores - valley planting site

S.W.R.I.S. Bore Number	Drillers Bore Number	Commencement of Operation	Bore Classification	Top of Inner Tube (AHD)	Natural Surface Level (AHD)	Bottom of Tube (AHD)	Length of Slotting (m)	Length of Inner Tube (m)	Height of T.O.I.T. Above N.S.L. (m)	Depth of B.O.T. Below N.S.L. (m)
61218050	1A-78	10/05/1978	Forest	278.775	278.275	277.075	1.00	1.700	0.500	1.200
61218051	1C-78	10/05/1978	Forest	278.759	278.260	247.589	2.30	31.170	0.499	30.671
61218052	2A-78	10/05/1978	Forest	264.095	263.600	262.400	1.00	1.695	0.495	1.200
61218053	2B-78	10/05/1978	Forest	264.104	263.600	258.604	1.00	5.500	0.504	4.996
61218054	2C-78	10/05/1978	Forest	264.095	263.600	247.595	5.00	16.500	0.495	16.005
61218055	C-79	19/03/1979	Forest	274.725	274.240	254.885	3.00	19.840	0.485	19.355
61218056	11-79	19/03/1979	Reforest	268.306	267.770	255.166	3.00	13.140	0.536	12.604
61218057	C-79	19/03/1979	Reforest	268.347	267.760	241.797	3.00	26.550	0.587	25.963
61218058	1-79	19/03/1979	Reforest	266.688	265.920	264.708	1.00	1.980	0.768	1.212
61218059	3-79	19/03/1979	Reforest	266.514	266.010	255.814	3.00	10.700	0.504	10.196
61218060	2-79	19/03/1979	Reforest	266.521	266.050	260.701	1.00	5.820	0.471	5.349
61218061	C-79	19/03/1979	Reforest	266.513	266.030	247.093	9.00	19.420	0.483	18.937
61218062	6-79	20/03/1979	Reforest	267.508	266.970	256.898	3.00	10.610	0.538	10.072
61218063	7-79	20/03/1979	Pasture	272.639	272.120	259.368	3.00	13.270	0.519	12.751
61218064	10-79	20/03/1979	Pasture	277.931	277.430	262.691	3.00	15.240	0.501	14.739
61218065	C-79	20/03/1979	Pasture	277.981	277.430	243.231	6.20	34.750	0.551	34.199
61218066	C-79	20/03/1979	Forest	286.866		267.976	3.00	18.890		
61218067	4-79	20/03/1979	Reforest	267.278	266.800	256.968	3.00	10.310	0.478	9.832
61218068	5-79	20/03/1979	Forest	262.615	262.090	248.905	3.00	13.710	0.525	13.185
61218069	SITE10	07/08/1979	Forest	292.220	291.540	2720520	3.00	19.700	0.680	19.020

(1) T.O.I.T. = Top of inner tube
(2) B.O.T. = Bottom of tube

16. DATA ANALYSES AND INTERPRETATION OF RESULTS

6.1 Rainfall

Annual rainfall has been analysed in terms of hydrological water year i.e. 1982 rainfall refers to 1/4/82-31/3/83. During the study period (1980-89), rainfall varied between 473 mm yr^{-1} and 910 mm yr^{-1}. The average rainfall for the period of 655 mm yr^{-1} was 8% lower than the long term average (1926-88) of 713 mm yr^{-1}. Only three years (1981, 1983 and 1988) had rainfall higher than the long term average. Most of the rainfall (more than 80%) occurred in between May and October.

6.2 Groundwater Levels Beneath the Native Forest

Three bores, located along the south-west boundary of the catchment, were used to observe changes in groundwater levels beneath native forest. The minimum groundwater level for each year for all forest bores are shown in Table 3a. The variation of yearly minimum relative to 1980, averaged for the three bores, is shown in Fig. 4. During 1980-89 there was a net rise of 1.19 m.

Table 3b presents the annual maximum groundwater levels of all forest bores. The variation in maximum groundwater level was similar to the minimum levels. Over the 1980-89 period, there was a net rise of 1.41 m.

The minimum groundwater level which occurs in autumn appears to be influenced by the rainfall of the preceding year. To determine the effect of annual rainfall variation, a linear regression of change in mean minimum groundwater level (Y, mm yr^{-1}) relative to the previous year's rainfall (X, mm) was derived. The resulting equation is:

$$y = -1170 + 1.989X \qquad (1)$$

$$r^2 = 0.82,\ p\ \tilde{}0.001$$

Table 3a:Yearly minimum water level (m AHD) for observation bores in native forest

Bore No.	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
G61218051	254.359	254.559	254.979	255.169	255.679	255.699	255.719	255.359	255.009	255.159
G61218054	252.475	252.795	253.695	253.325	253.925	254.095	254.155	253.895	253.475	254.095
G61218068	252.503	250.845	251.275	251.225	251.615	251.815	251.995	251.915	251.615	253.69

Table 3b:Yearly maximum groundwater level (m AHD) for observation bores in native forest

Bore No.	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
G61218051	254.769	254.909	255.419	255.659	255.819	255.959	255.979	255.759	255.359	255.859
G61218054	253.195	253.685	254.075	254.555	254.595	254.975	254.645	254.395	254.645	254.895
G61218068	252.98	251.245	251.595	251.805	251.965	252.275	252.365	252.215	252.215	254.390

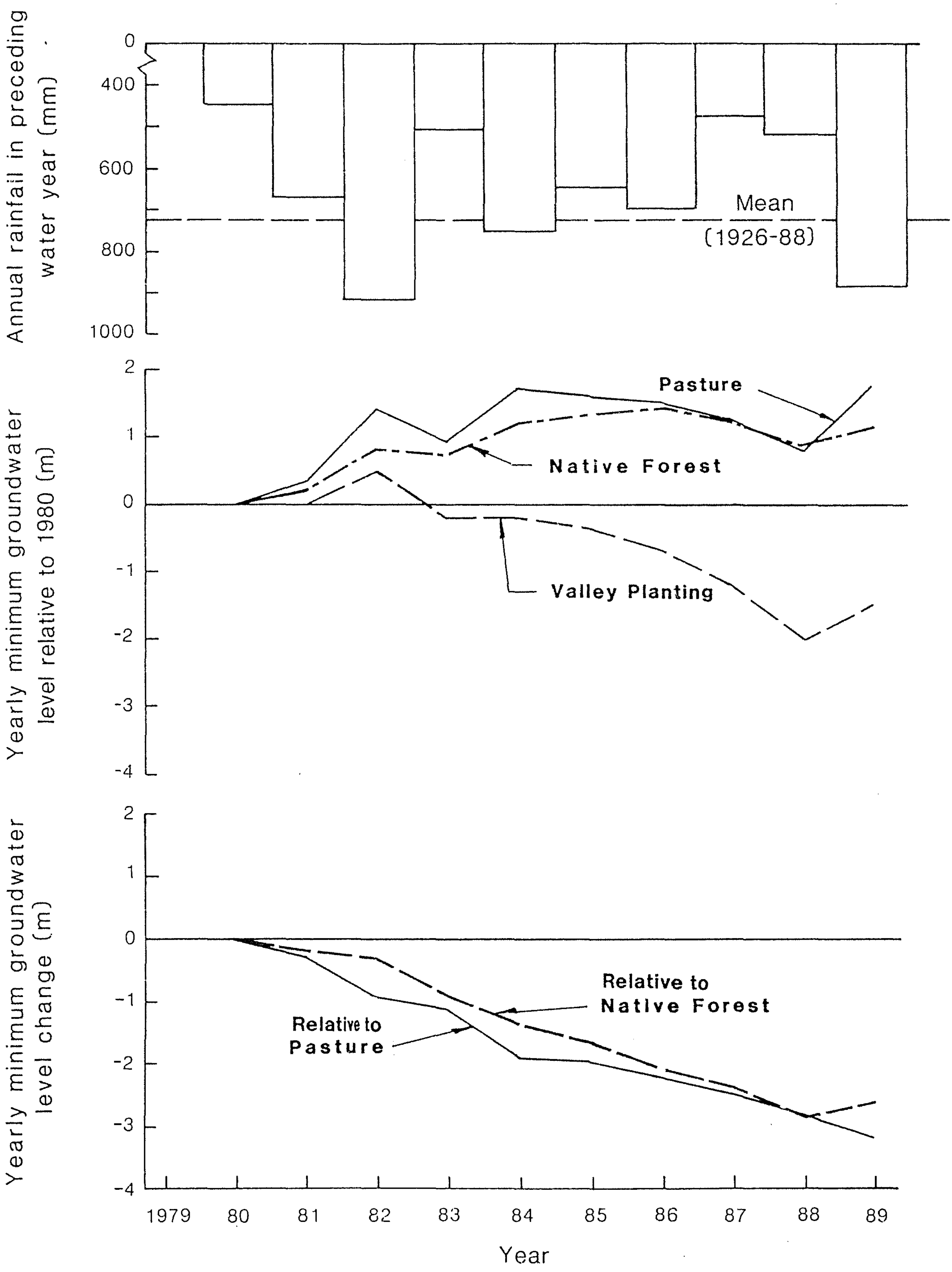


Figure 4:Annual rainfall and minimum groundwater level at the valley planting site

The above equation predicts a 250 mm yr^{-1} rise in minimum groundwater level under long term average rainfall conditions (Fig. 5a).

As the maximum groundwater level occurs soon after the winter rains (in the same year), the annual change in maximum groundwater level (Y, mm yr^{-1}) was plotted against the rainfall of the same year (X, mm). The regression is:

$$Y = -1613 + 0.456X \qquad (2)$$
$$r^2 = 0.1$$

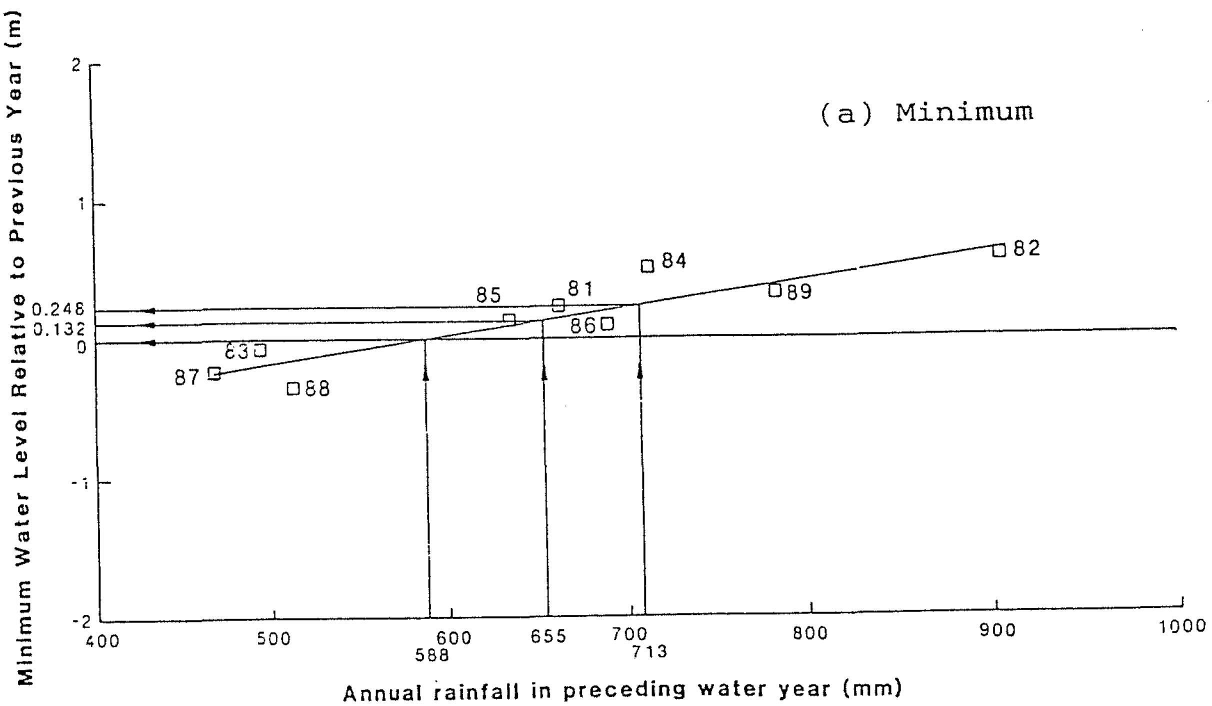
The lower coefficient of determination (r^2) and slope of the above equation suggest the maximum groundwater levels observed in the native forest showed little response to the annual rainfall. The regression is therefore not a good predictor of groundwater level change (Fig. 5b).

6.3 Groundwater Levels beneath Pasture

Hydrographs for the fives bores at the control site are shown in Appendix A. Hydrographs of all bores were also plotted together to show the similarity in trends (Fig. 6).

The annual minimum groundwater levels of all pasture bores are given in Table 4a. The variation in the annual minimum groundwater level relative to 1980, averaged for the five bores is shown in Fig. 4. For three years (1982, 1984 and 1989) the groundwater levels increased due to significantly above average rainfall in the preceding year. Over the whole period there was a net rise in the minimum groundwater table of 1.8 m.

The annual maximum groundwater level for all pasture bores are shown in Table 4b. The maximum groundwater level rose in the high rainfall years of 1983 and 1989 and fell in other years (Fig. 7). Over the 1980-89 period there was a net rise in maximum groundwater level of 2.0 m.



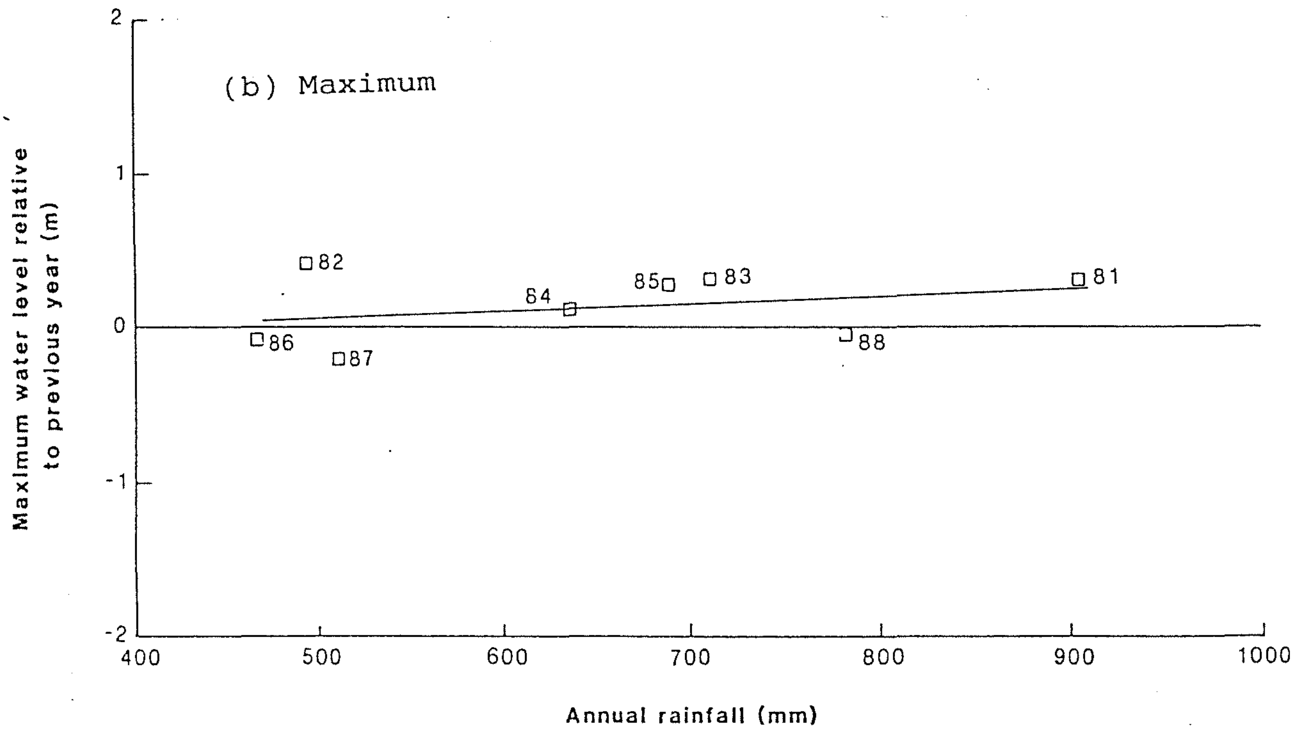


Figure 5: Relationship between groundwater level and annual rainfall - Forest Bores

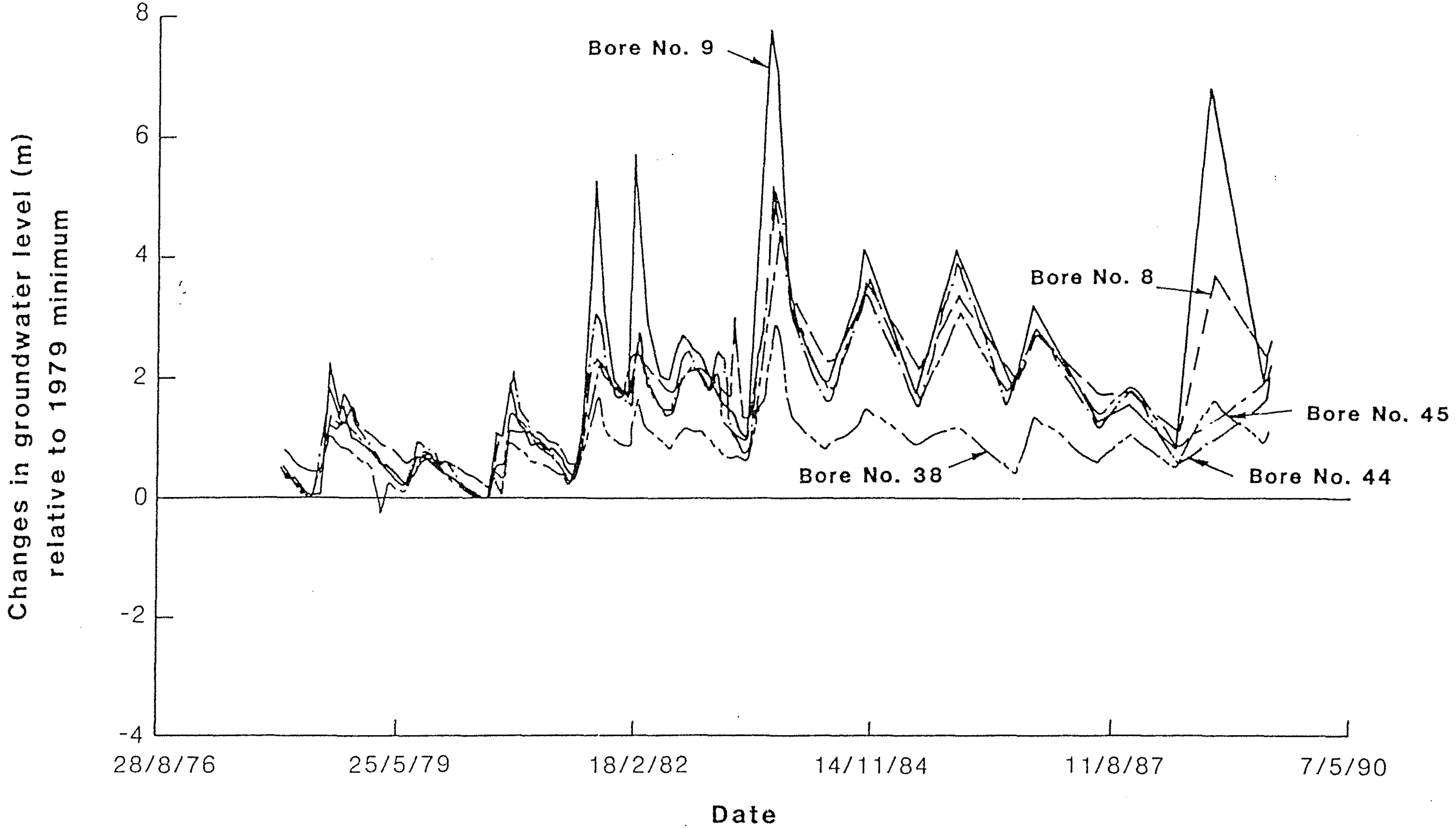


Figure 6: Groundwater levels at pasture site relative to 1980 minimum level

Table 4a: Yearly minimum water level (m AHD) for observation - pasture site

Bore No.	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
G61218008	281.167	281.767	283.157	282.677	283.767	283.587	283.387	283.117	282.387	283.767
G61218009	279.522	279.852	281.172	280.522	281.462	281.272	281.302	280.792	280.332	281.492
G61218038	275.527	275.757	276.297	276.097	276.297	276.367	275.907	276.057	276.007	276.407
G61218044	277.510	277.690	278.820	278.160	278.980	278.880	278.940	278.610	278.010	278.960
G61218045	279.482	279.752	280.942	280.452	281.362	281.162	281.342	280.962	280.412	281.512

Table 4b: Yearly maximum groundwater level (m AHD) for observation - pasture site

Bore No.	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
G61218008	282.487	283.837	283.997	287.087	285.297	285.027	284.267	283.167	285.357	285.267
G61218009	281.462	284.802	285.242	287.302	283.662	283.682	282.742	281.092	286.342	284.942
G61218038	276.437	277.117	277.157	278.257	276.947	276.657	276.807	276.507	277.057	277.207
G61218044	279.470	280.320	280.060	282.250	280.700	281.210	280.060	279.160	278.010	280.460
G61218045	280.992	281.882	281.982	284.052	283.272	282.702	282.362	281.462	280.412	282.962

To determine the effect of annual rainfall variation, a linear regression of change in the mean minimum groundwater level (Y, mm yr^{-1}) relative to the previous year on rainfall (X, mm) was derived, with the result:

$$y = -2403 + 3.97X \qquad (3)$$
$$r^2 = 0.83,\ p \sim 0.001$$

Equation (3) predicts yearly minimum groundwater levels would rise 430 mm yr^{-1} under long term average rainfall conditions; and would be stable if the preceding year's rainfall was 605 mm (Fig. 8a).

A similar regression of change in maximum groundwater level against rainfall of the same year had the form:

$$y = -3384 + 5.424X \qquad (4)$$
$$r^2 = 0.40,\ p \sim 0.03$$

The low r^2 and p indicate that equation (4) would be a poor predictor for maximum groundwater level change (Fig. 8b).

6.4 Groundwater Level Response to Reforestation

Trees planted on agricultural pastures have the potential to decrease the vertical recharge to the aquifer system by increasing transpiration and interception loss (Eastham et al., 1988; Schofield, 1990). Analyses of annual minima and maxima and comparisons to the control site and native forest were carried out to determine the effects of reforestation on groundwater levels. A typical representation of groundwater level fluctuation beneath the native forest, pasture and valley planting sites is shown in Fig. 9.

6.4.1 Minimum Groundwater Level

The annual minimum groundwater levels for all bores at the valley planting site are shown in Table 5a.

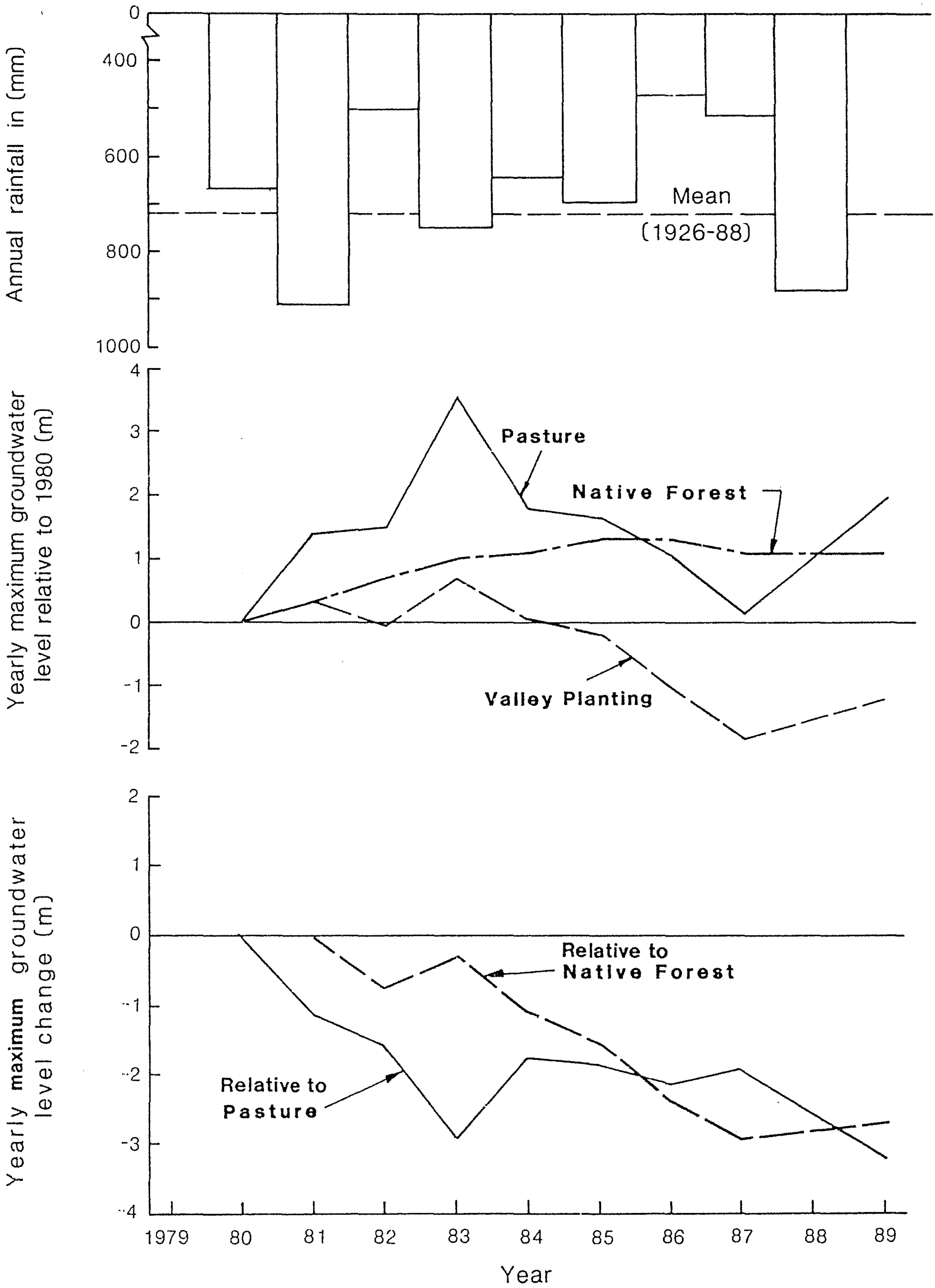


Figure 7:Annual rainfall and maximum groundwater level at the valley planting site

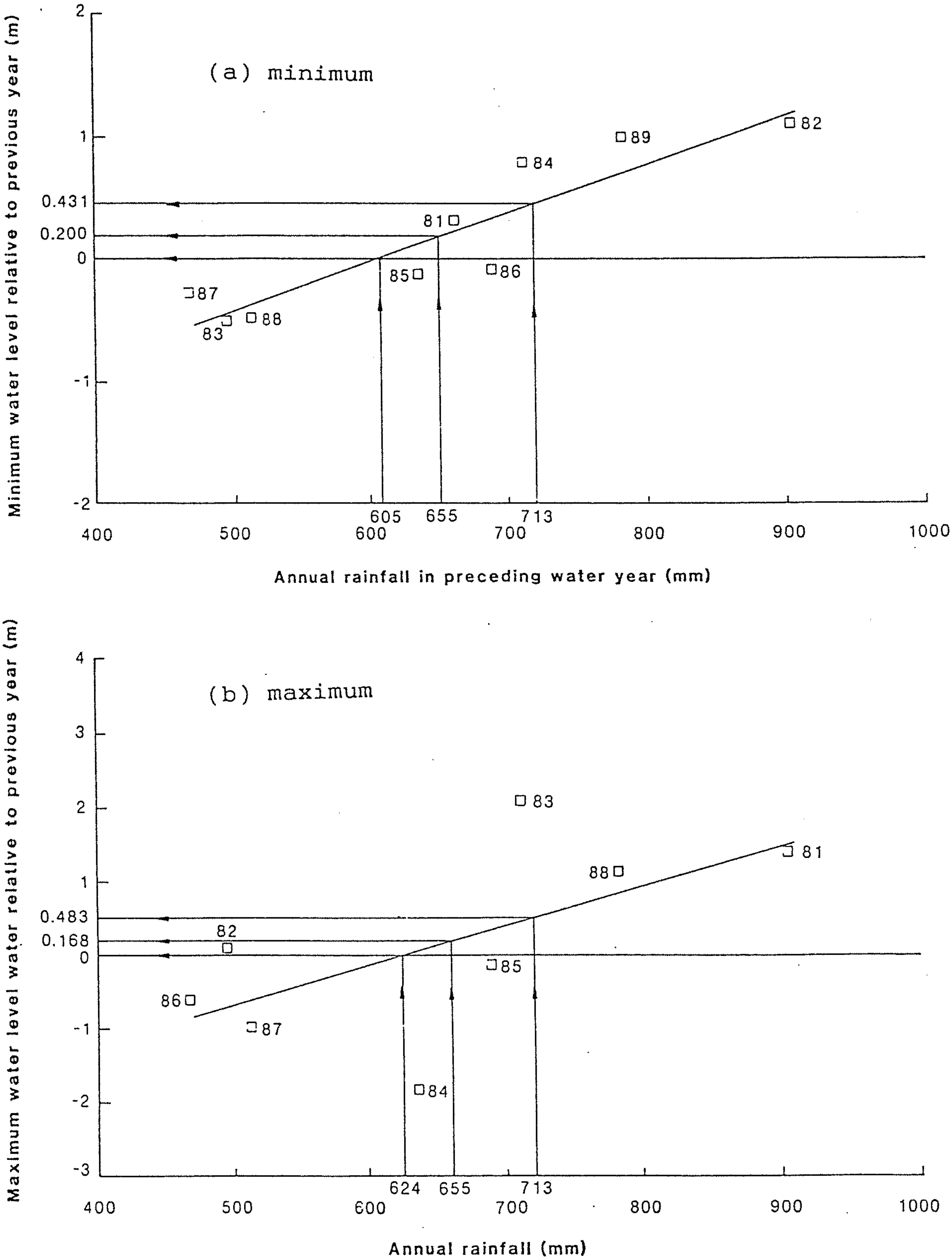


Figure 8:Relationship between groundwater level and annual rainfall - Pasture Bores

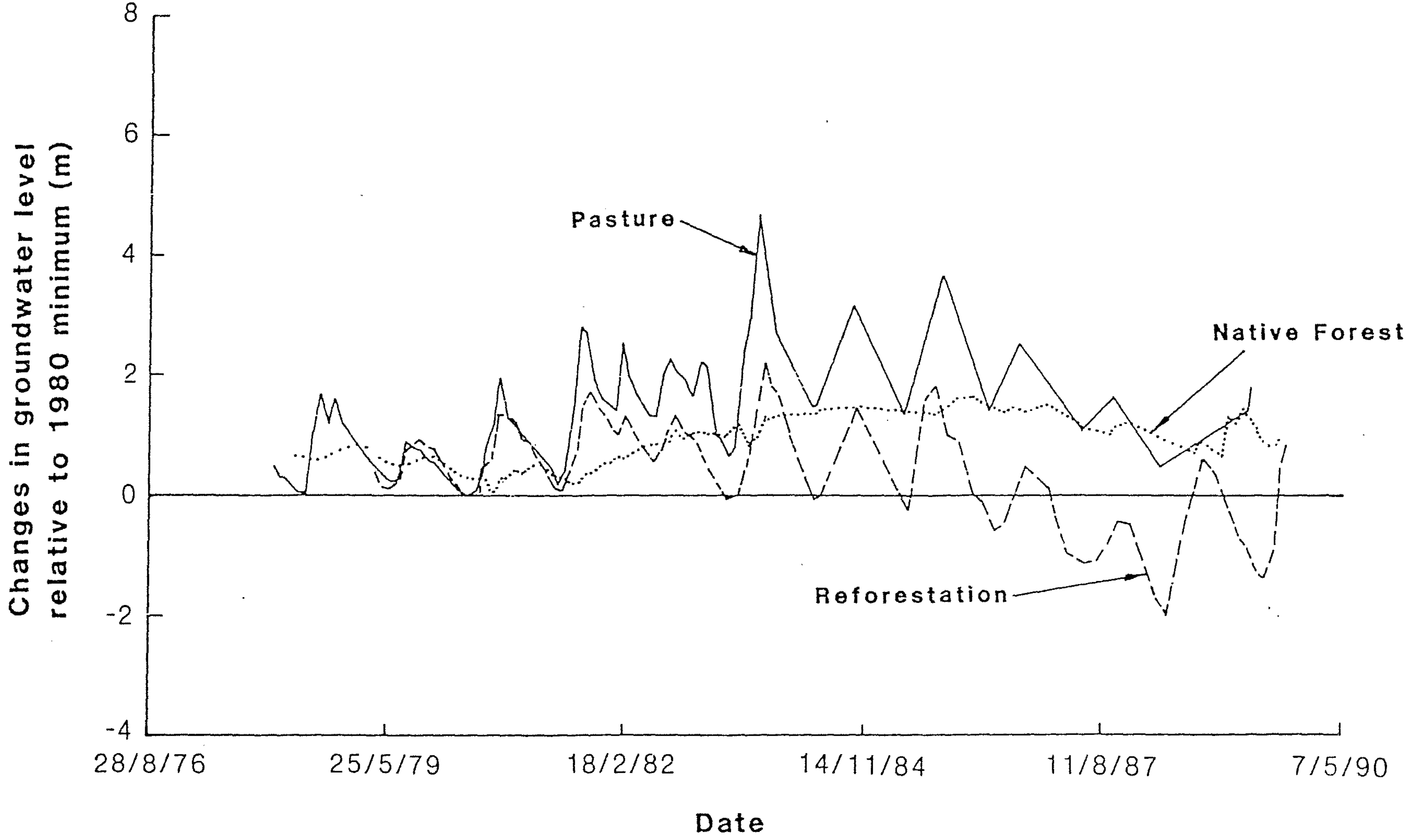


Figure 9: Typical groundwater hydrographs at pasture, forest and valley planting sites

Fig. 4 shows that the high rainfall in 1981 (910 mm), resulted in groundwater levels rising beneath the control, valley planting and the forest sites during 1982. However, these rises were 0.31 m less than that beneath the native forest, and 0.93 m less than that beneath the control site. The following year had very low rainfall (497 mm). Groundwater levels of all sites declined, but in relative terms the decline was near-uniform (Fig. 4). Between 1984 and 1987 annual rainfall was below the long term average. The annual rainfalls ranged from 470 mm to 693 mm. During this period, the water level under the valley planting had near-linear decline relative to native forest and pasture bores. Above average rainfall was recorded in 1988. As a result the water table rose at the native forest, pasture and valley planting site. Over the study period, the minimum groundwater level beneath reforestation declined 3.25 m relative to pasture; and 2.65 m relative to the native forest.

6.4.2 Maximum Groundwater Level

The yearly maximum groundwater levels for bores at the valley planting site are given in table 5b.

The variation in maximum groundwater level is shown in Fig. 7. In 1981, the water level under pasture rose by 1.4 m following an above average rainfall year (910 mm). But under the reforestation and native forest, the maximum groundwater level rose by 0.31 m and 0.30 m respectively. Annual rainfall was very low in 1982. The maximum water level under pasture was steady, under reforestation it declined and under native forest it increased slightly. In 1983, the maximum groundwater level at the control site rose by 2.1 m, but surprisingly at the valley planting site and beneath the native forest the increase was 0.7 m and 1.0 m respectively. The marked decline of 1.4 m relative to pasture did not continue in the following year. Indeed further changes in groundwater level were similar relative to pasture during the period 1984-87. In contrast, the maximum water level

Table 5a: Yearly minimum groundwater level (m AHD) for observation - valley planting site

Bore No.	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
G61218056	262.146	262.176	262.706	261.926	262.086	261.826	261.516	260.906	260.146	260.706
G61218059	261.921	261.971	262.451	261.711	261.821	261.611	261.301	260.721	259.921	260.421
G61218062	261.858	261.938	262.448	261.818	261.798	261.618	261.298	260.758	259.888	260.508
G61218067	264.848	264.838	265.198	264.628	264.438	264.368	264.048	263.578	262.798	263.278

Table 5b: Yearly maximum groundwater level (m AHD) for observation - valley planting site

Bore No.	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
G61218056	263.556	263.856	263.506	264.296	263.526	263.086	262.206	261.606	263.006	262.006
G61218059	263.201	263.491	263.171	263.941	263.271	262.861	262.171	261.421	262.181	261.821
G61218062	263.208	263.608	263.208	264.078	263.358	263.708	262.358	261.458	262.508	262.708
G61218067	266.258	266.488	266.098	266.718	266.298	265.878	265.278	264.478	264.578	264.878

steadily declined relative to the native forest (Fig. 7). At the end of the study period, the maximum groundwater reduction was 3.20 m relative to pasture and 2.61 m relative to native forest.

6.4.3 Comparison of Minimum and Maximum Groundwater Level Reduction

In Fig. 10, the reductions of yearly minimum and maximum water levels relative to the pasture are shown. The minimum groundwater level had a near-linear decline over the study period. Maximum groundwater level reduction was more variable with a sudden decrease in 1983 and subsequent recovery in 1984 and then another marked decline in 1989.

Fig. 11 shows the comparison of the reduction of minimum and maximum groundwater level relative to the native forest. Both the minimum and maximum water table reduction were closely matched.

6.4.4 Regression Analyses

Linear regressions were developed to predict the changes in minimum and maximum groundwater levels under different annual rainfall conditions.

The linear regression between the annual rainfall (X, mm) and changes in minimum groundwater level relative to previous year (Y, mm yr^{-1}) is:

$$y = -1670 + 2.389X \qquad (5)$$

$$r^2 = 0.646, \; p \sim 0.001$$

Under long term average rainfall conditions, the above equation predicts a fall in water level of 30 mm yr^{-1}. For the minimum groundwater table to be stable, the preceding year's rainfall would need to be 770 mm (Fig. 12a).

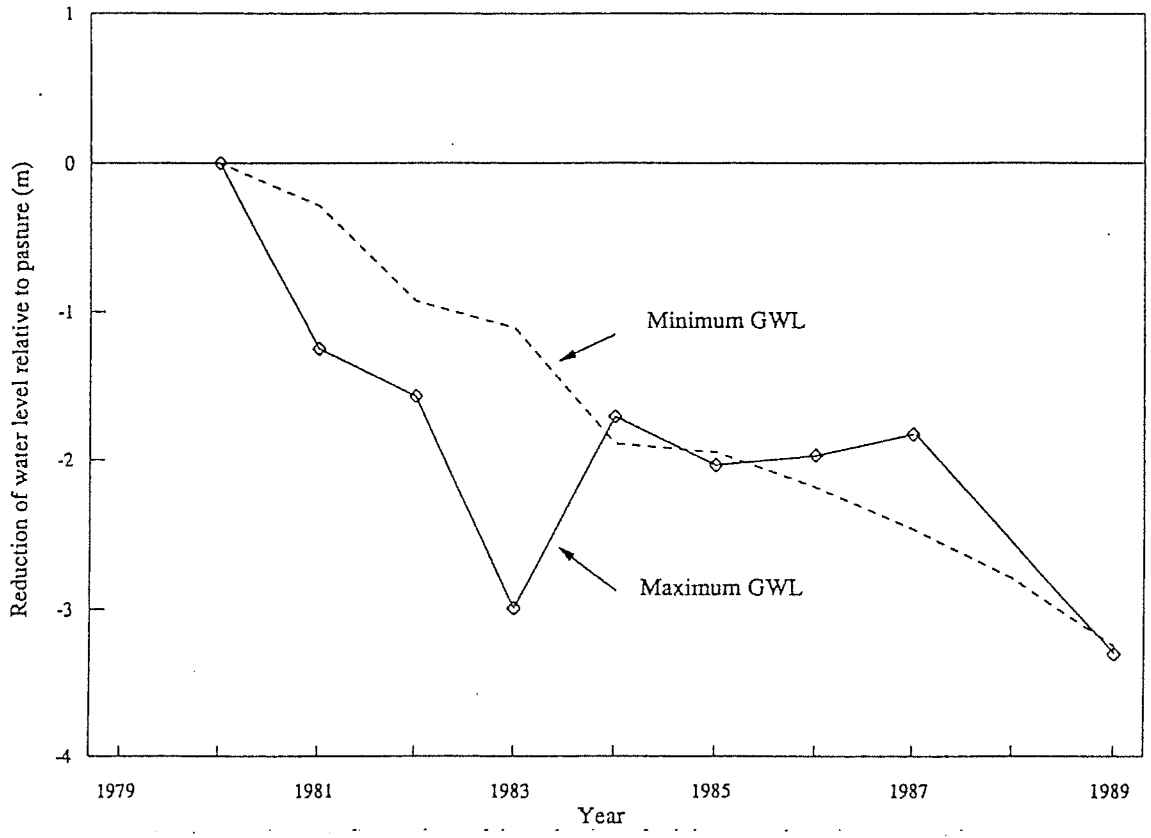


Figure 10:Comparison of the reduction of minimum and maximum groundwater level relative to pasture

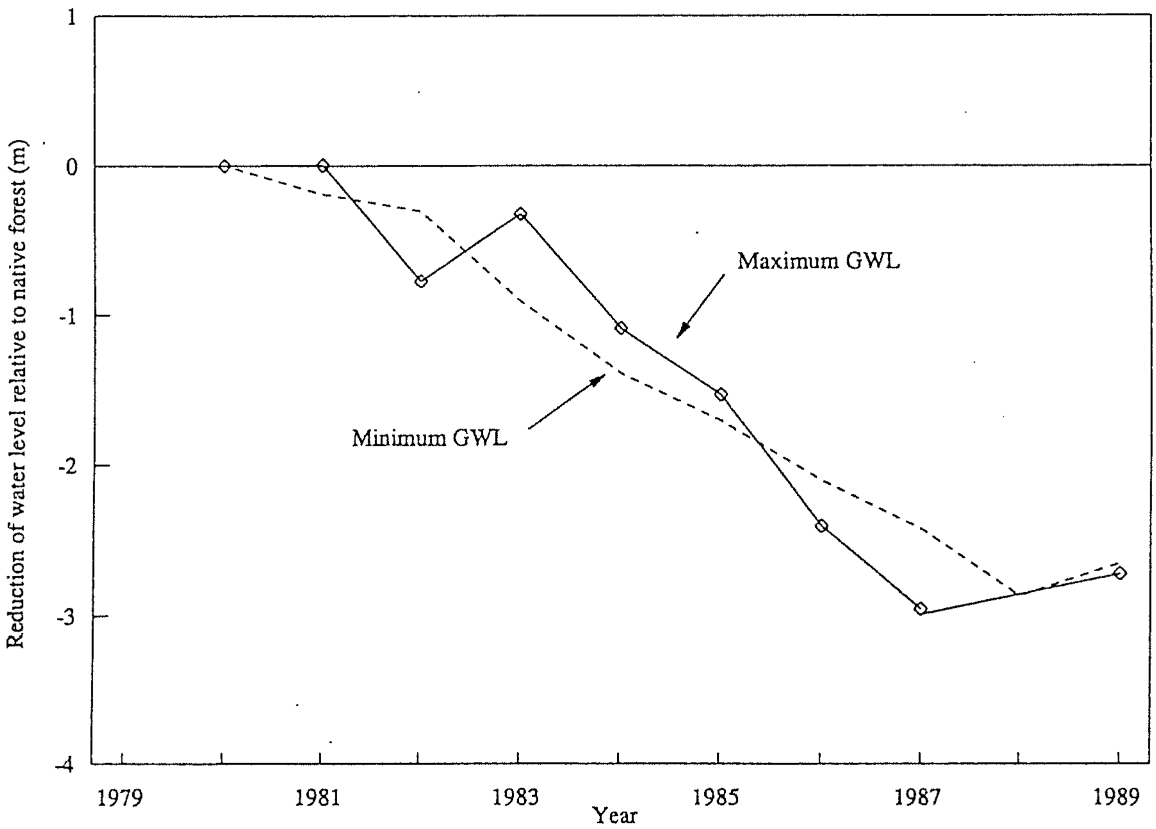


Figure 11:Comparison of the reduction of minimum and maximum Groundwater Level relative to native forest

The linear regression between the change in maximum water level (Y, mm yr^{-1}) and the annual rainfall (X, mm) is:

$$Y = -2292 + 3.324X \qquad (6)$$

$$r^2 = 0.659, p \sim 0.001$$

If the long term average rainfall (713 mm yr^{-1}) was to occur, the water level would rise 80 mm yr^{-1}. The maximum groundwater level would have remained stable if the annual rainfall is 662 mm (Fig. 12 b).

6.4.5 Groundwater Levels at the Nested Piezometers

Fig. 13 shows the changes in groundwater levels for piezometer nest 61218060-61 located near the Bingham river at the valley planting site. In the initial years following planting a downward vertical gradient existed in bores 60 and 61. However, in the latter years, groundwater levels decreased due to increases in evapotranspiration. As groundwater level reduced, the gradient reversed after 1982.

The other piezometer nest (bores 61218056-57), located just 80 m upslope of the first nest, showed a similar response (Fig. 14). Initially no vertical gradient was evident, but in the latter years the drop in groundwater levels resulted in a substantial upward gradient.

6.5 Comparison of Valley Cross-section Potentiometric Surface

Fig. 15 shows the temporal variation in the potentiometric surfaces across the bore transect 61218066-69. Three years (1980, 1985 and 1989) have been plotted as an example. There has been very little change in water level

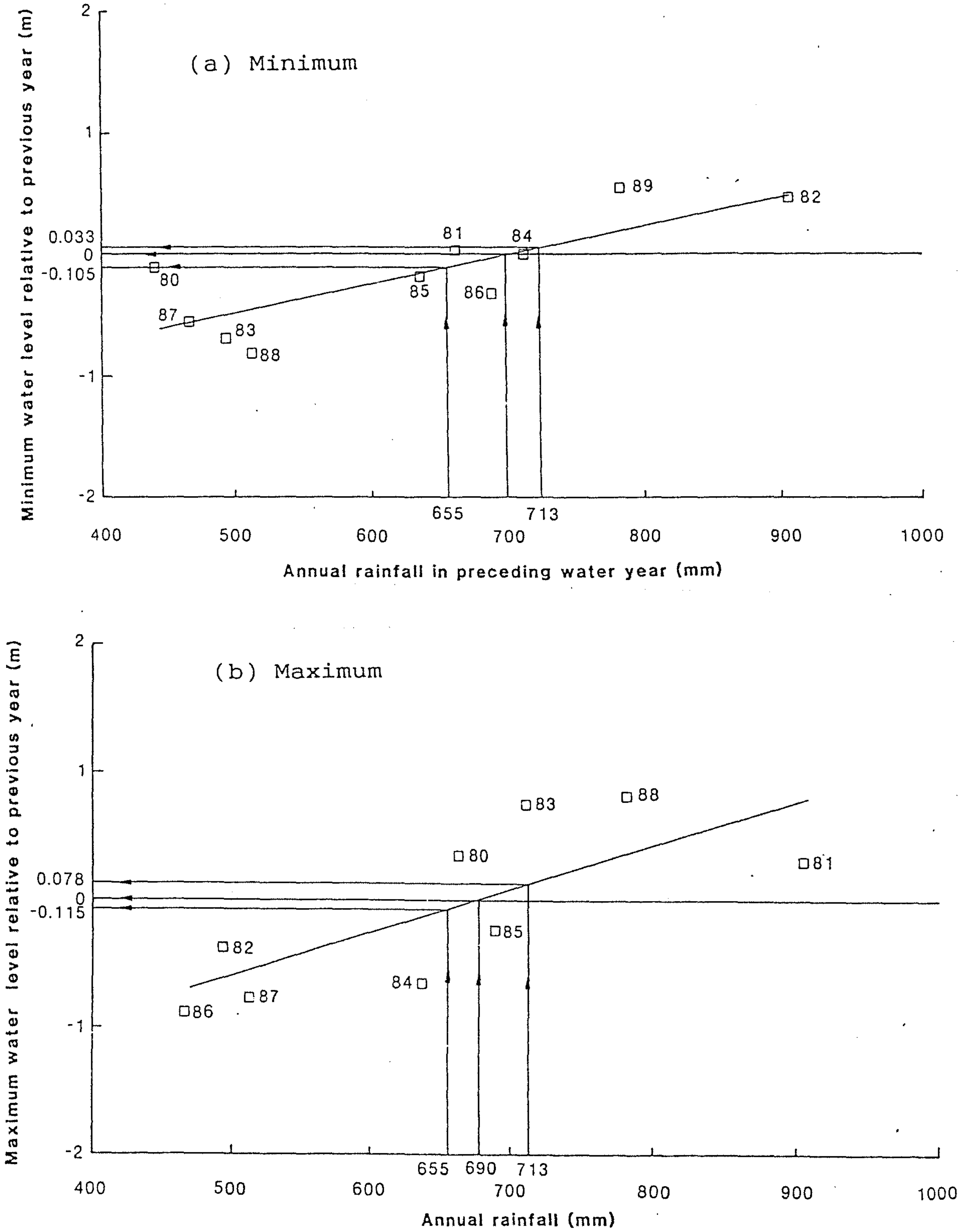


Figure 12: Relationship between groundwater level and annual rainfall - valley reforestation bores

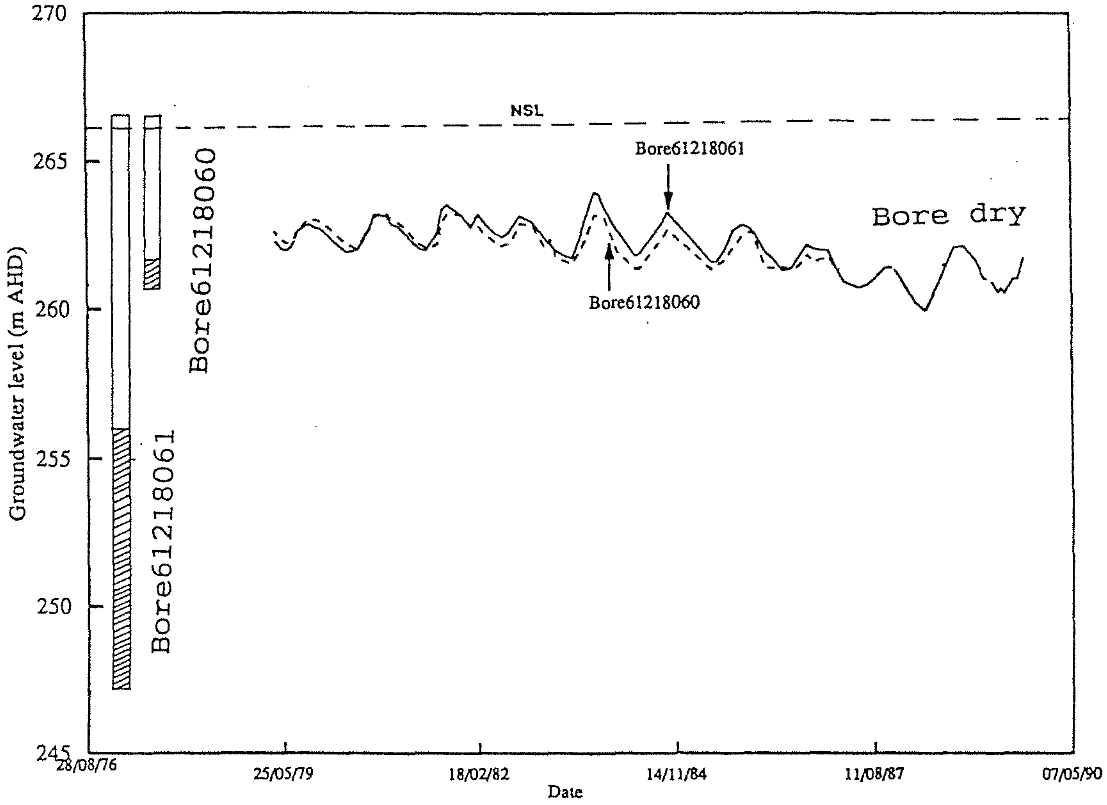


Figure 13:Groundwater hydrographs in piezometer nest 61218058-61

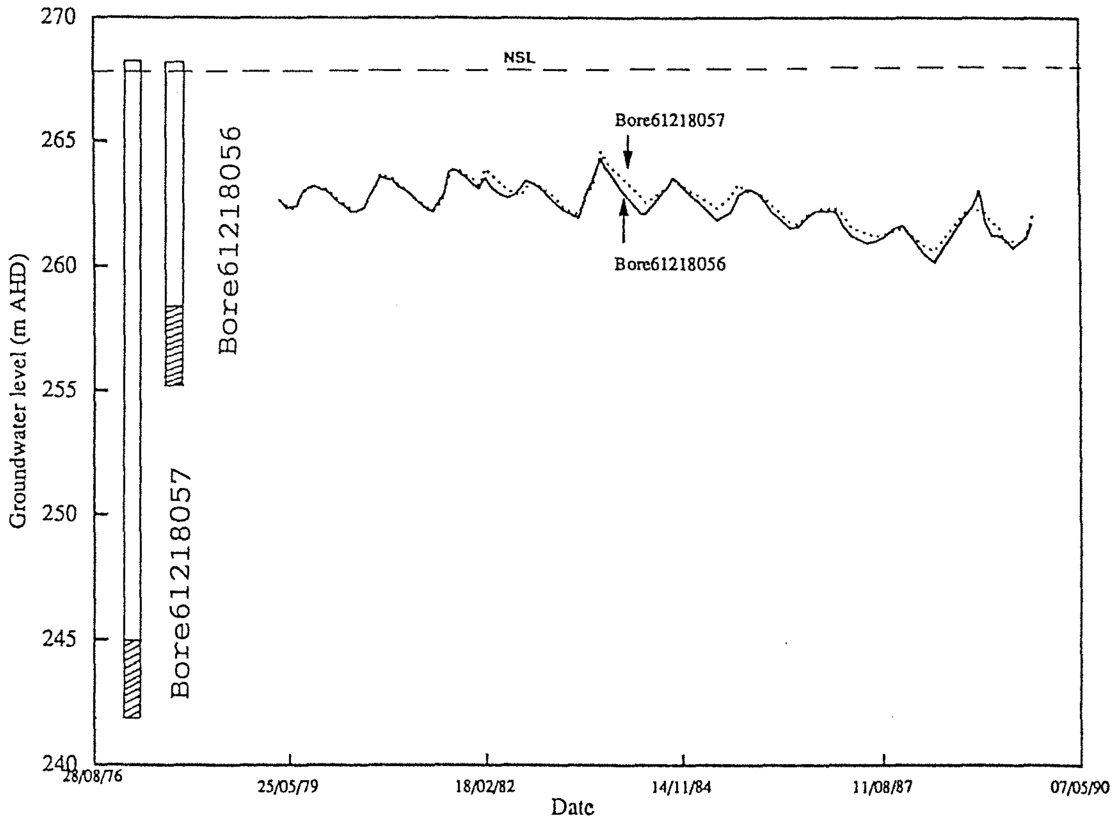


Figure 14:Groundwater hydrographs in piezometer nest 61218056-57

beneath the native forest, a net reduction beneath the reforested area and a net increase under pasture. This figure shows that the groundwater system is responding to the type of the overlying vegetation.

6.6 Groundwater Flow Characteristics

There are too few bores at the valley planting site to determine groundwater flow directions. However, Fig. 15, a cross-section along the bore transect, shows a downslope flow towards the stream which has been maintained over the study period.

6.7 Groundwater Salinity

6.7.1 Groundwater Salinity Trends beneath Native Forest

The groundwater salinities of all forest bores are shown in Appendix A. Analysis of monthly insitu samples shows there is considerable temporal variation in salinity. As experienced in other experimental sites (Bari, et al., 1990) these data were considered unreliable. To overcome this, all bores were developed on May 30, 1989, then a pumped sample collected and analysed in the laboratory.

Salinity data were analysed in two categories:

(a) Bores screened at the water table
(b) Bores screened below the water table

The results from the samples taken on 30/5/89 were compared with results from samples taken on 6/5/80. Table 6 indicates the average reduction in groundwater salinity for all bores was 13.3%.

6.7.2 Groundwater Salinity Trends beneath Pasture

The groundwater salinity for each of the bores at the pasture site is shown in Appendix A. The salinity data from the pumped

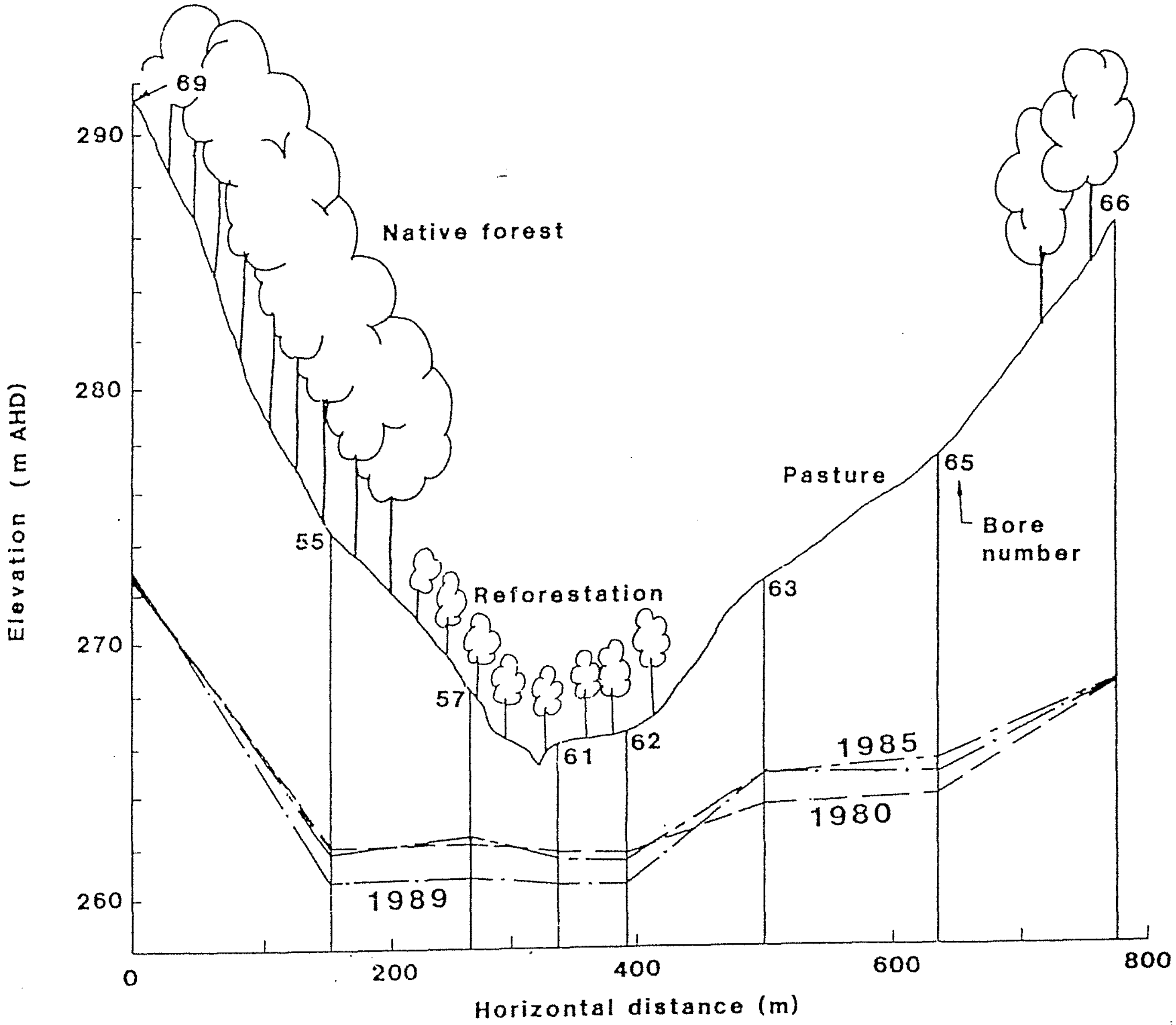


Figure 15:Comparison of valley cross-section potentiometric surfaces of 1980, 1985 and 1989

Table 6 : Salinity variations - bores in native forest

Bore group	Bore No.	Salinity (mg L^{-1}) om 6/5/80	Average	Salinity (mg L^{-1}) 30/5/89	Average	% Change in Salinity Indiv.	Average
Screened at Water Table	61218068	10370.0	10370.0	8965.0	8965.0	-13.55	-13.55
Screened	61218051	3607.0		3600.0		-0.19	
Not at Water Table	61218054	4917.0	4262.0	3808.0	3704.0	-22.55	-13.09
All			6298.0		5457.7		-13.34

samples were analysed into two categories:

(a) Fresh bores
(b) Saline bores

Results from samples taken on 16/5/89 were compared with results from samples taken on 6/5/80. Table 7 indicates the average reduction in salinity for all bores was 41%. The average reduction in the fresh bores was 34% and 61% in the saline bores.

6.7.3 Groundwater Salinity Trends Beneath Reforestation

The groundwater salinities for bores at the valley planting site are also shown in Appendix A. The salinity data from the pumped samples were also classified into two groups:

(a) Bores screened at water table
(b) Bores screened below water table.

Results from pumped samples taken on 30/5/89 were compared with the results from samples taken on 6/5/80. Table 8 indicates the salinity of all bores were reduced by an average of 30%. One of the bores had a 23% increase in salinity, while the other three had reductions, varying from 44% to 70%. The bore group screened at water table averaged a 38% reduction and the group screened below water table, 16%.

Distribution of Soil Salt Content

The soil salinity profiles of bores 61218057, 61 and 65 measured in 1979 and 1989 are shown in Fig. 18. Bore 61 is located at the valley floor (Fig. 2). Soil salt storage has increased in this bore, particularly in the unsaturated zone. This increase may be due to the accumulation of salts leached from the upslope pasture area. In contrast, soil salt storage in bore 57 remained stable. Bore 65 is situated in pasture on mid slope. Groundwater level has risen at this site and soil salt storage of the unsaturated zone has decreased slightly, probably due to the leaching of salts (Fig. 18c).

Table 7 : Salinity variations - pasture bores

Bore Classification	Bore No.	Salinity ($mg\ L^{-1}$) on 6/5/80	Average	Salinity ($mg\ L^{-1}$) on 16/5/89	Average	% Change in Salinity Indiv.	Average
Fresh	61218008	229.0	313.0	210.0	206.5	-8.3	-34.02
	61218009	397.0		203.0		-48.87	
Saline	61218038	3093.0		1776.0		-42.58	
	61218044	4915.0	3798.0	2828.0	2244.67	-42.46	-60.90
	61218045	3386.0		2130.0		-37.09	
All			2404.0		1429.4		-40.54

Table 8 : Salinity variations - valley planting bores

Bore Classification	Bore No.	Salinity ($mg\ L^{-1}$) on 6/5/80	Average	Salinity ($mg\ L^{-1}$) 30/5/89	Average	% Change in Salinity Indiv.	Average
Screened at	61218059	6960.0	8058.0	4906.0	5013.0	-29.51	-37.78
Water Table	61218062	9156.0		5120.0		-44.08	
Screened	61218056	2439.0		470.0		-69.66	
Below	61218067	4078.0	3258.5	5018.0	2744.0	23.05	-15.79
Water Table							
All			5658.3		3946.0		-30.26

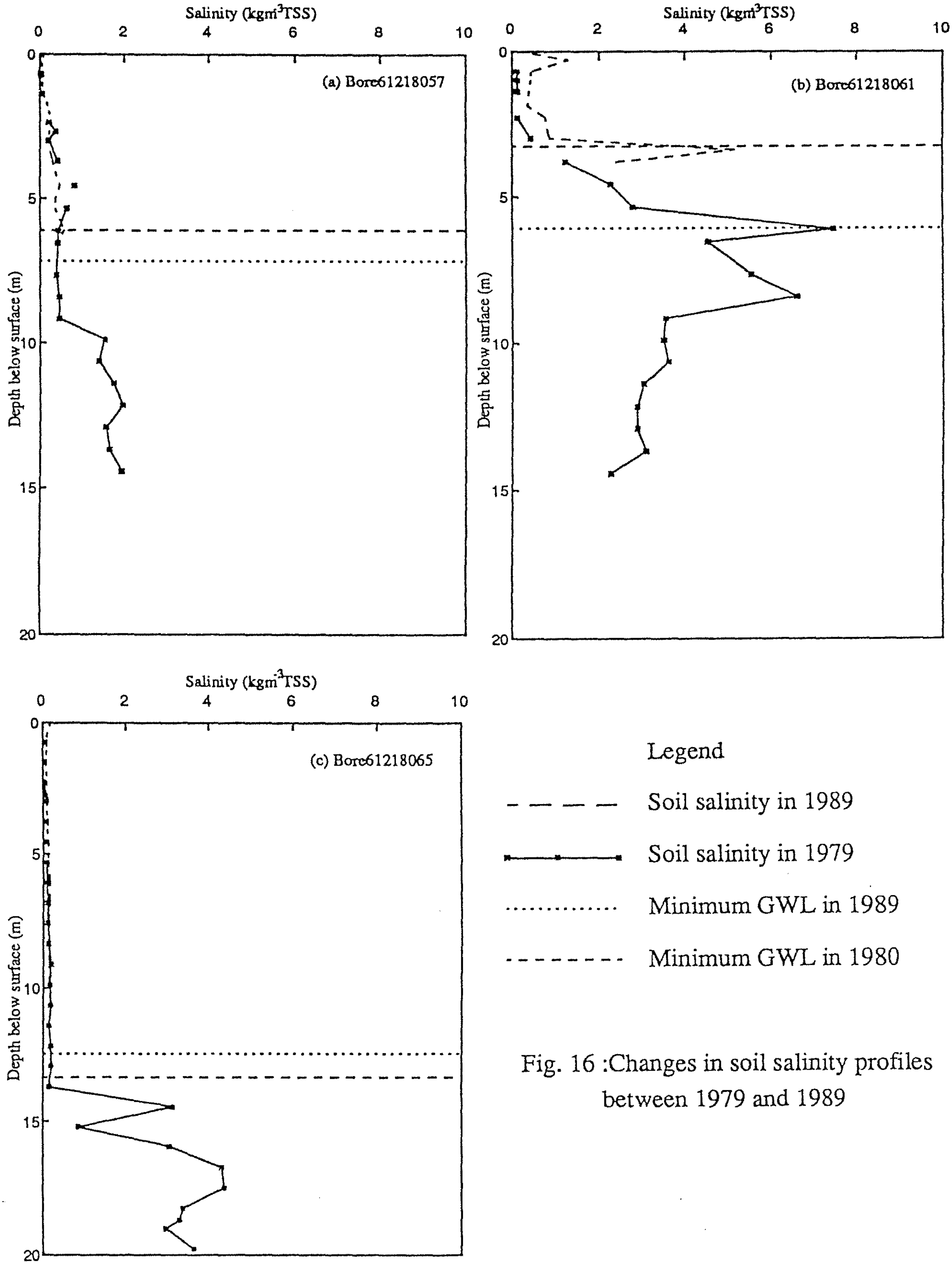


Fig. 16 :Changes in soil salinity profiles between 1979 and 1989

7. DISCUSSION

7.1 The Effect of Rainfall on Groundwater Level

It is clear in this study that groundwater level is highly responsive to the annual rainfall, particularly when groundwater levels are reasonably close to the ground surface (beneath reforestation and pasture control in this case). During the study period, the mean annual rainfall was 8% lower than the long term average (1926-88). Had long term average rainfall conditions prevailed, the regression analysis indicated groundwater levels would have risen beneath both sites. The rise would have been less under valley planting than pasture. On the other hand, if the drying climate for south-west Western Australia occurs due to the Greenhouse Effect (Pittock, 1988), than the lower rainfall would increase the rate of water table decline.

7.2 Suitability of Pasture Control

Two aspects of the pasture control site are undesirable. Firstly the site has 14% strip reforestation in its catchment which may have some time varying influence on the upslope control bores. The second undesirable feature is the location of the control bores upslope of the valley floor (to avoid strip reforestation) where their depths to water table and salinities are different to the valley planting reforestation bores. These problems should be considered as uncertainties in the comparative analyses.

7.3 Limitations of Linear Regressions

The regression analyses for groundwater level beneath valley planting site implies that changes in groundwater level are dependent only on rainfall, i.e. independent of tree crown cover, rooting depth, depth to groundwater etc. These other variables are time dependent and are not easily identifiable. Therefore, the regressions should be considered indicative only.

7.4 Groundwater Salinity

7.4.1 Salinity Beneath Native Forest

The groundwater salinity beneath the native forest declined during the study period. This reduction of 13% suggests that the export of salts from the saturated zone is slightly higher than accession from the unsaturated zone.

7.4.2 Salinity Beneath Pasture Site

Analysis of the monthly samples shows a considerable temporal variation in salinity (Appendix A). However, as experienced with other experimental sites (Bari et al., 1991), the salinity data are considered unreliable. The apparent variation of salinity is probably caused by fresh water leakage from the unsaturated aquifer at the time of intensive rainfall and/or improper sampling. Analysis of the pumped samples shows a 41% reduction over nine years. If the present rate continues, the salinity would be below 1000 mg L^{-1} TSS in a relatively short period of time. Most analyses of solute leaching from a soil indicate an exponential decay of salt with time (Mulqueen and Kirkham, 1972). However, Peck (1973) notes a near-linear decay in solute concentration in experiments on the displacement of a saline groundwater with increased but uniformly distributed recharge in an inclined soil slab. If this is the case at the control site on Stene's Farm, then serious attention should be given to further analysis of the rate of solute export and groundwater and stream salinity decline in agricultural systems which are in hydrological equilibrium.

7.4.3 Salinity Beneath Reforestation

The valley reforestation bores also had the problem of fresh water leakage at the time of high rainfall (Appendix A). So the salinity analysis was limited to comparing the data collected after pumping in 1989 with the data taken on May 1980. The result shows a 30% decrease over the study period. The significance of this result is that salinities have not increased as was assumed likely by a number of authors (Conacher, 1982; Morris and Thomson, 1983; Williamson, 1986). The decrease in groundwater salinity implies that solute leaching from the aquifer beneath the reforestation stand is occurring at faster rate than increasing concentration due to transpiration of the groundwater. In the situation of a declining groundwater table other processes will also affect groundwater salinity, such as solution-dissolution rates and solute deposition in the unsaturated zone.

7.5 Comparison of Valley Planting Site with Agroforesty Site

The effects of agroforestry on saline groundwater tables have been reported by Bari et al. (1991). The agroforestry site is located on the eastern side of the valley planting site. The physiography of the two sites are similar. Prior to the establishment of trees, 25% of the agroforestry site was cleared for pasture grazing compared to 44% of the valley planting. At both sites, reforestation took place in the valley floor. The initial mean annual salinity was 6600 mg L^{-1} for the agroforestry site and 5400 mg L^{-1} for the valley planting site. The principal species planted at the agroforesty site were E. camaldulensis (59% of the plantation), E. calophylla (1%), E. sargentii (30%) and E. wandoo (10%) whereas at the valley planting site species planted were E. rudis (55%), E. camaldulensis (19.4%), E. wandoo (17.8%), E. calophylla (1.2%) and E. globulus (6.6%).

At the agroforestry site 57% of the cleared area was planted at an initial stem density of 1250 sph and later thinned to 150 to 900 sph. Trees were planted at the valley planting site with an initial density of 625 sph covering 35% of the cleared farmland. Natural death reduced tree density such that in 1988 it varied from 150 sph to 550 sph. The average crown cover at the two sites were 25% (agroforestry) and 41% (valley planting).

The reduction in minimum groundwater level at the valley planting site (3.3 m) was greater than at the agroforestry site (2.0 m). This was probably due to the higher crown cover at the valley planting site. There was a 30% average reduction in groundwater salinity at the valley planting site, whereas at the agroforestry site it was only 6%.

7.6 Use of Valley Planting Strategy in Salinity Control

The results from this study have demonstrated that the valley planting strategy can lower saline groundwater tables across a valley floor within a 10 year period. However the rate of decline was fairly modest, 163 mm yr^{-1} over the study period. A number of measures could improve this performance, including the implementation of recharge control measures on the remaining farm land, replanting trees where they have failed or planting trees with higher transpiration rates. The relative value of these measures could be assessed by modelling (Schofield, 1990b). This would have direct relevance to an on-going large-scale reforestation programme based on this strategy in the Collie catchment (Loh, 1988).

8. CONCLUSIONS

Based on the analyses and interpretation of data, the following conclusions can be drawn:

8.1 Groundwater Level

(i) The valley reforestation strategy covering 35% of the cleared farm land (with final stem densities of 150-550 sph) has lowered the minimum groundwater level by 1.47 m relative to ground level, 3.25 m relative to pasture control and 2.65 m relative to the native forest. The relative reduction was near-linear with time.

(ii) Relative to the pasture control site and native forest, the maximum groundwater level reduction was 3.2 m and 2.61 m respectively.

(iii) During the study period, rainfall was 8% lower than the long term average. Had long term average rainfall conditions prevailed, groundwater levels under both valley planting and pasture would have risen. However, if the current drier climatic conditions continue, the groundwater levels would be expected to decline further. The decline would be greater beneath the valley reforestation.

8.2 Groundwater Salinity

(i) The spatial variation of groundwater salinity at both the valley planting and control sites was high (fresh to highly saline).

(ii) During the study period, the groundwater salinity under valley planting decreased by 30%.

(iii) The groundwater salinity beneath pasture decreased by about 40% and about 10% under native forest over the study period. This result merits further investigation of solute leaching in moderate to high rainfall zones.

9. RECOMMENDATIONS

- To identify the effects of further crown and tree growth, bore monitoring should be continued to obtain yearly minimum and maximum groundwater levels.

- Sampling should be continued by the specified pumping evacuation method, twich a year to identify groundwater quality when the groundwater levels are its annual minima and maxima.

- To support interpretation of the groundwater data, tree covers should be measured in approximately 5 year intervals.

10. ACKNOWLEDGEMENTS

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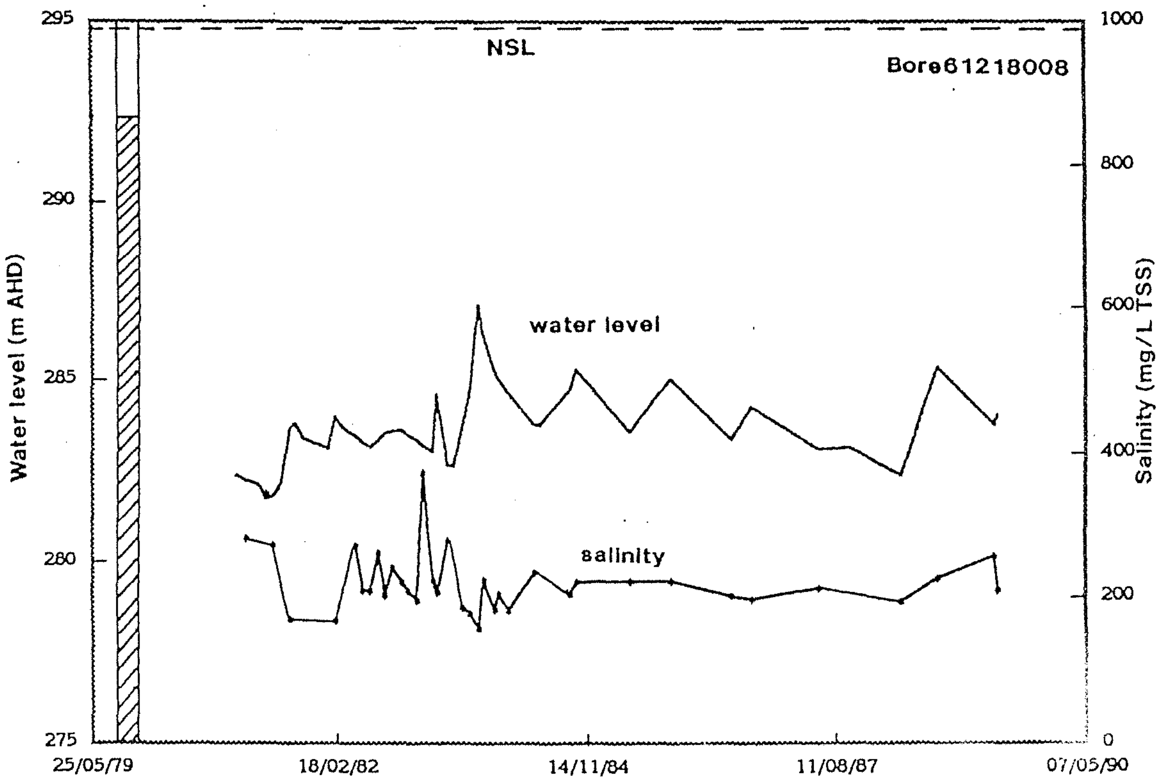
APPENDIX A

Groundwater Level and Salinity
Time Series for each forest,
control and reforested bore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Bore61218008
water level
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14/11/84
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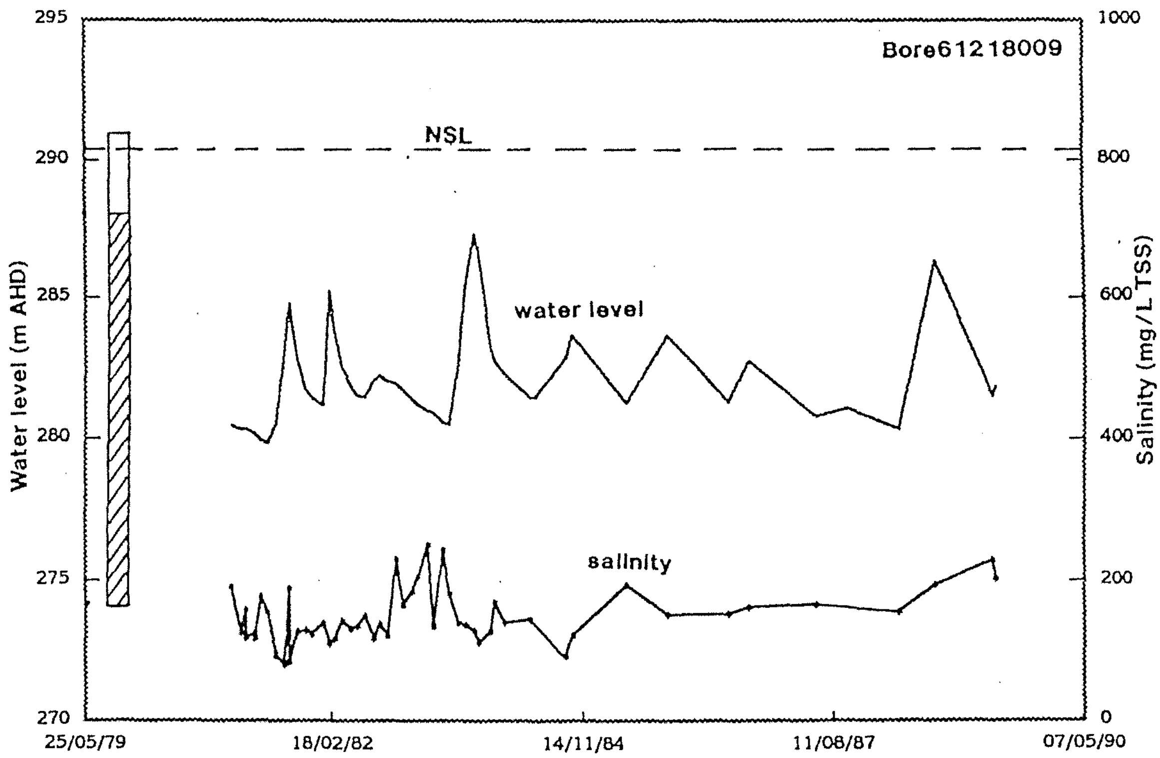
07/05/90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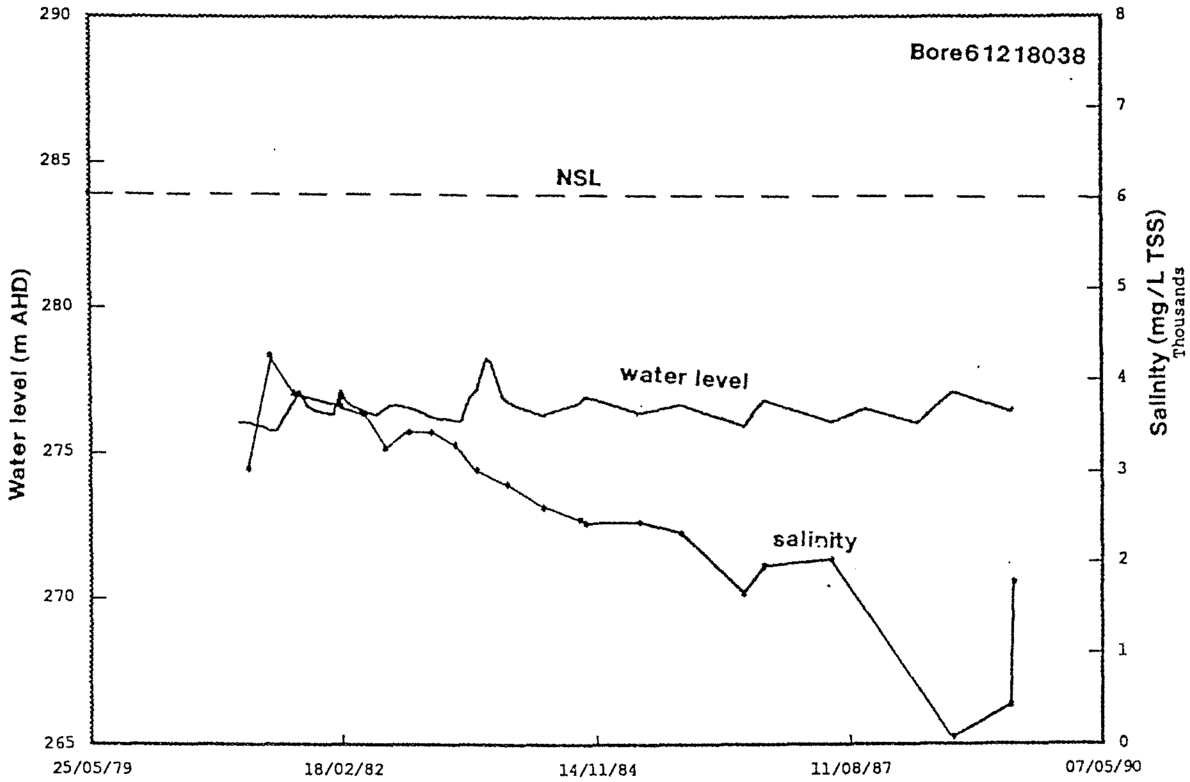
Bore61218038
NSL
water level
salinity
Water level (m AHD)
Salinity (mg/L TSS) Thousands
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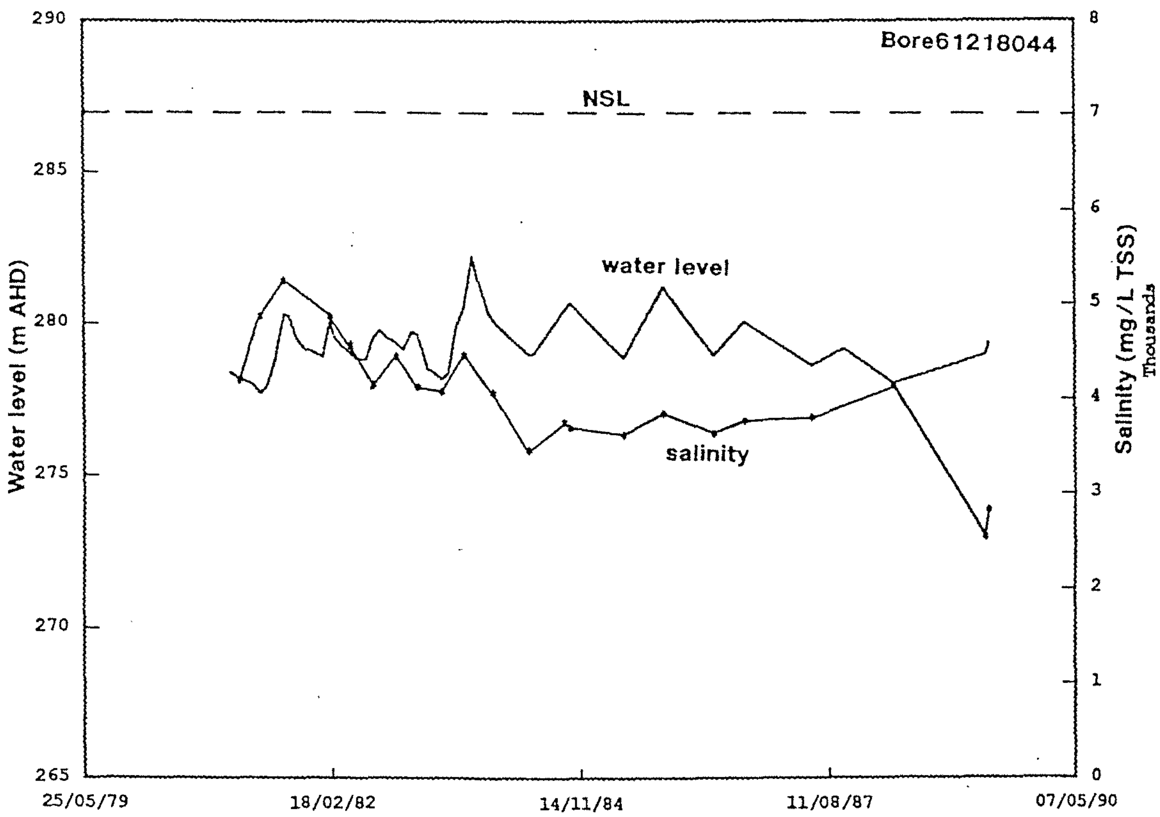
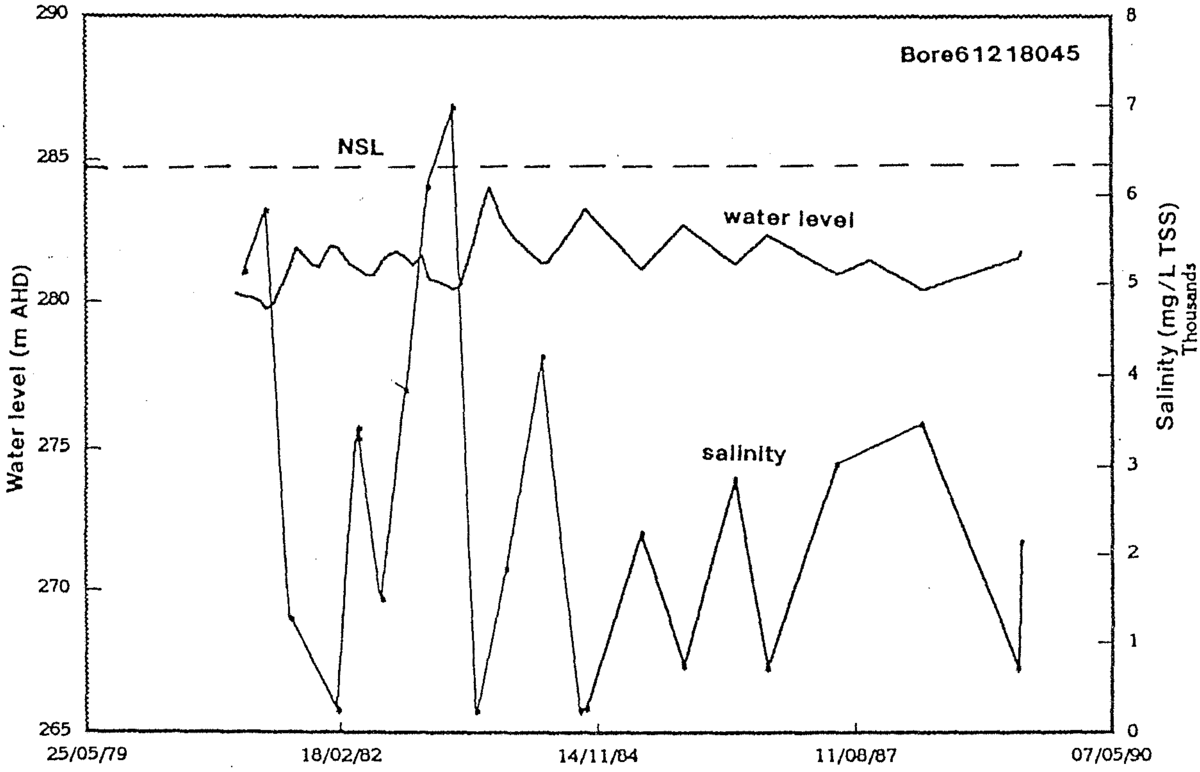
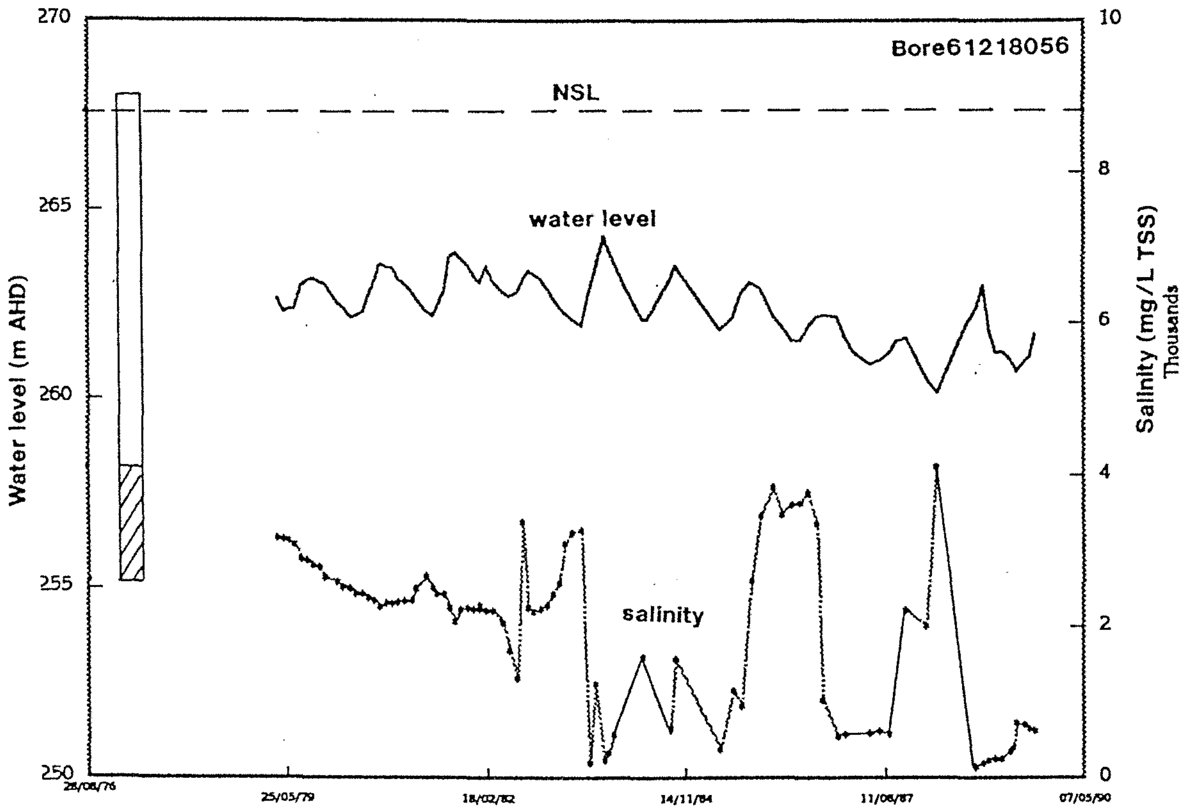
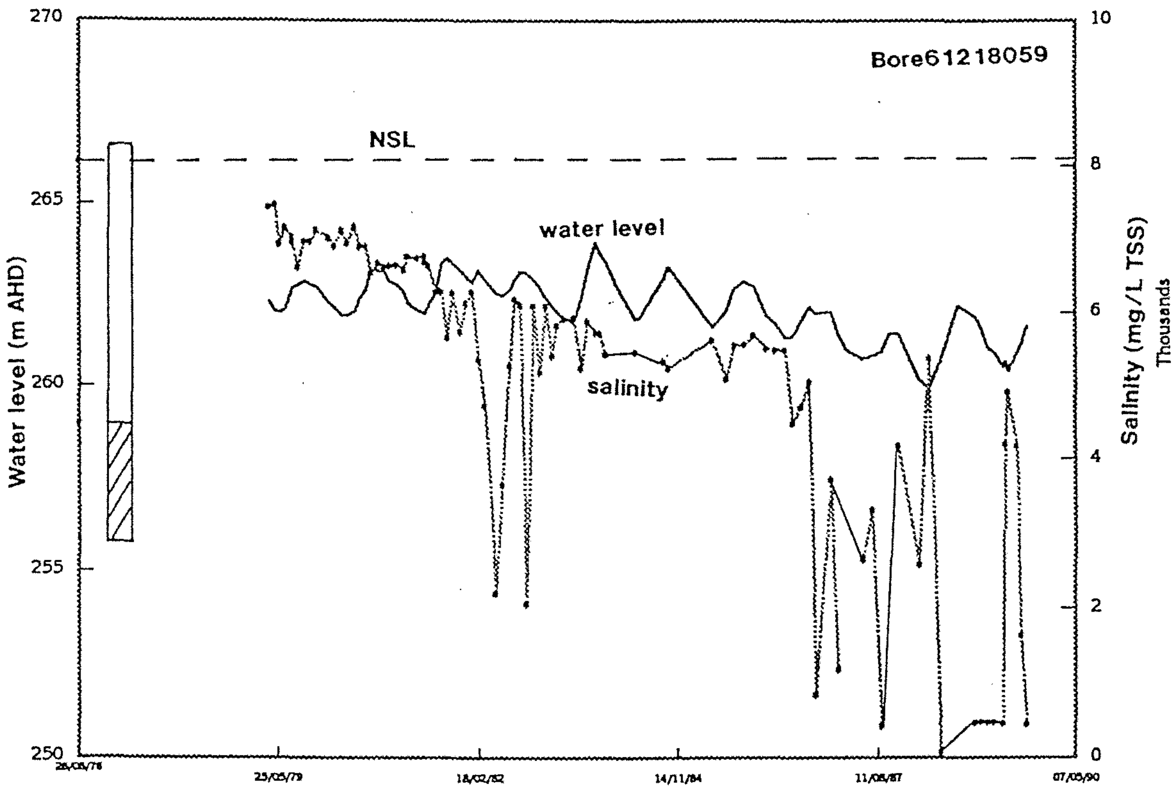
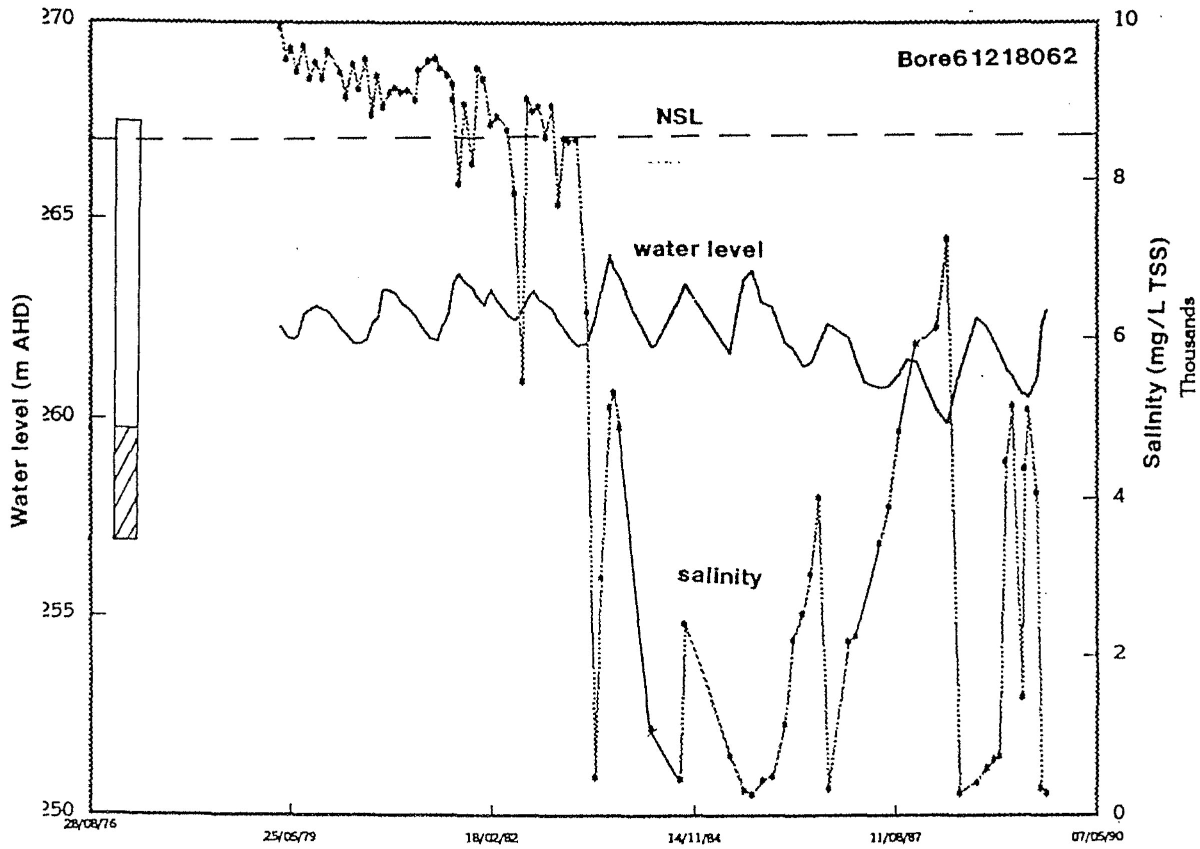
280
275
270
265
8
7
6
5
4
3
2
1
0
25/05/79
18/02/82
14/11/84
11/08/87
07/05/90

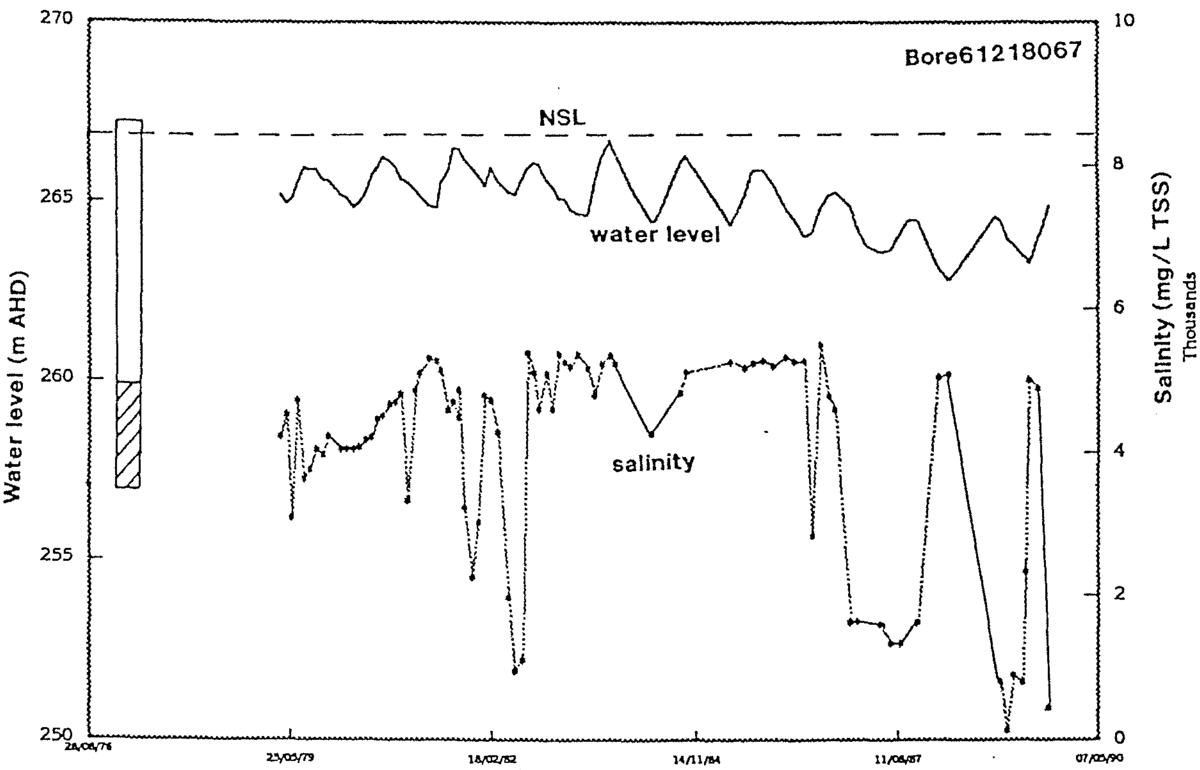

Bore61218044
NSL
water level
salinity
Water level (m AHD)
Salinity (mg/L TSS) Thousands
290
285
280
275
270
265
8
7
6
5
4
3
2
1
0
25/05/79
18/02/82
14/11/84
11/08/87
07/05/90

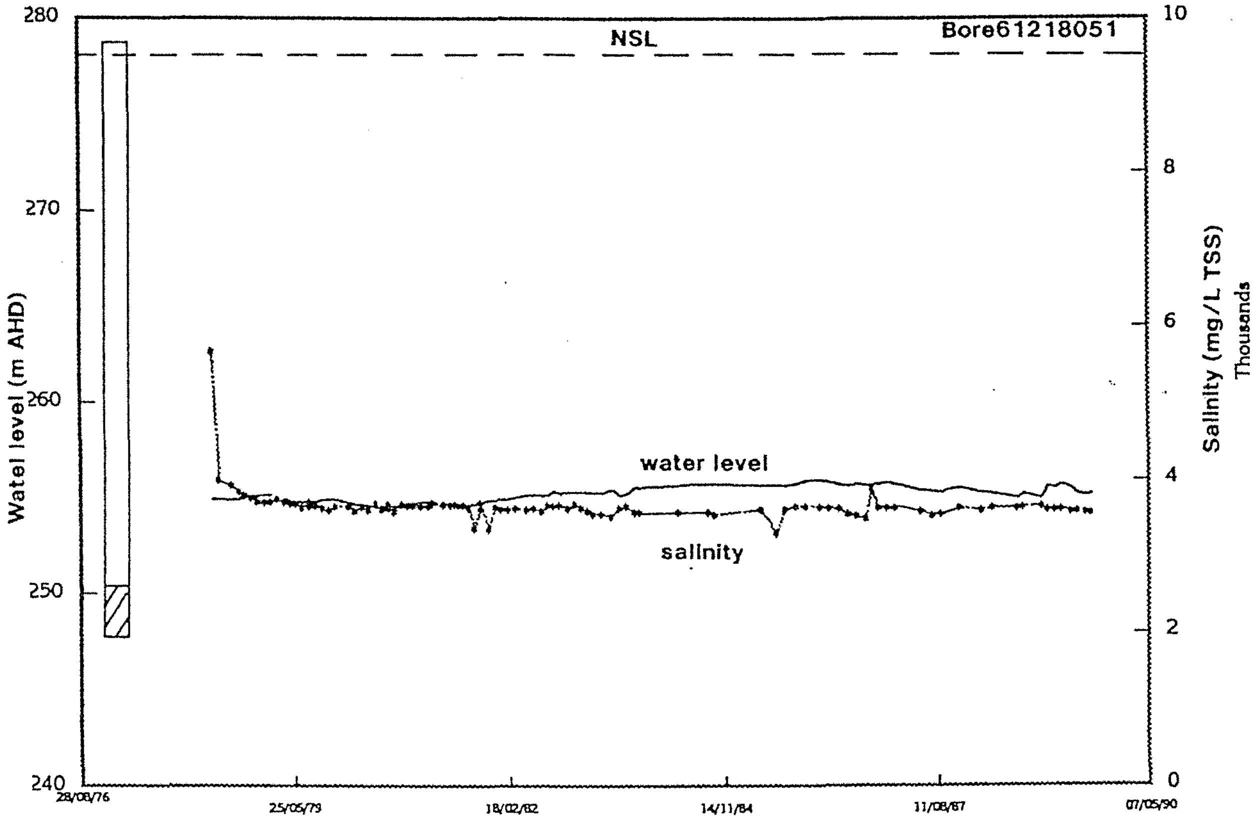

Bore61218045
NSL
water level
salinity
Water level (m AHD)
Salinity (mg/L TSS) Thousands
290
285
280
275
270
265
8
7
6
5
4
3
2
1
0
25/05/79
18/02/82
14/11/84
11/08/87
07/05/90

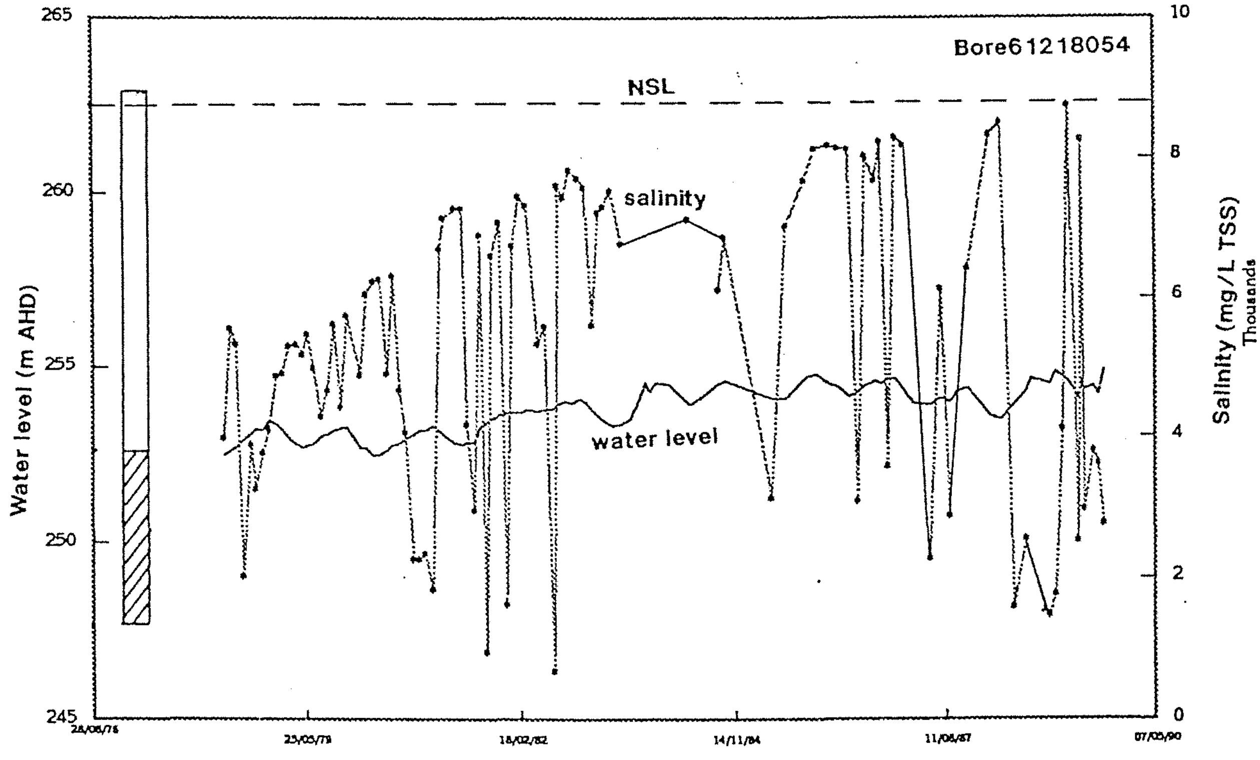

Bore61218056
NSL
water level
salinity
Water level (m AHD)
Salinity (mg/L TSS)
Thousands
270
265
260
255
250
10
8
6
4
2
0
28/08/76
25/05/79
18/02/82
14/11/84
11/08/87
07/05/90

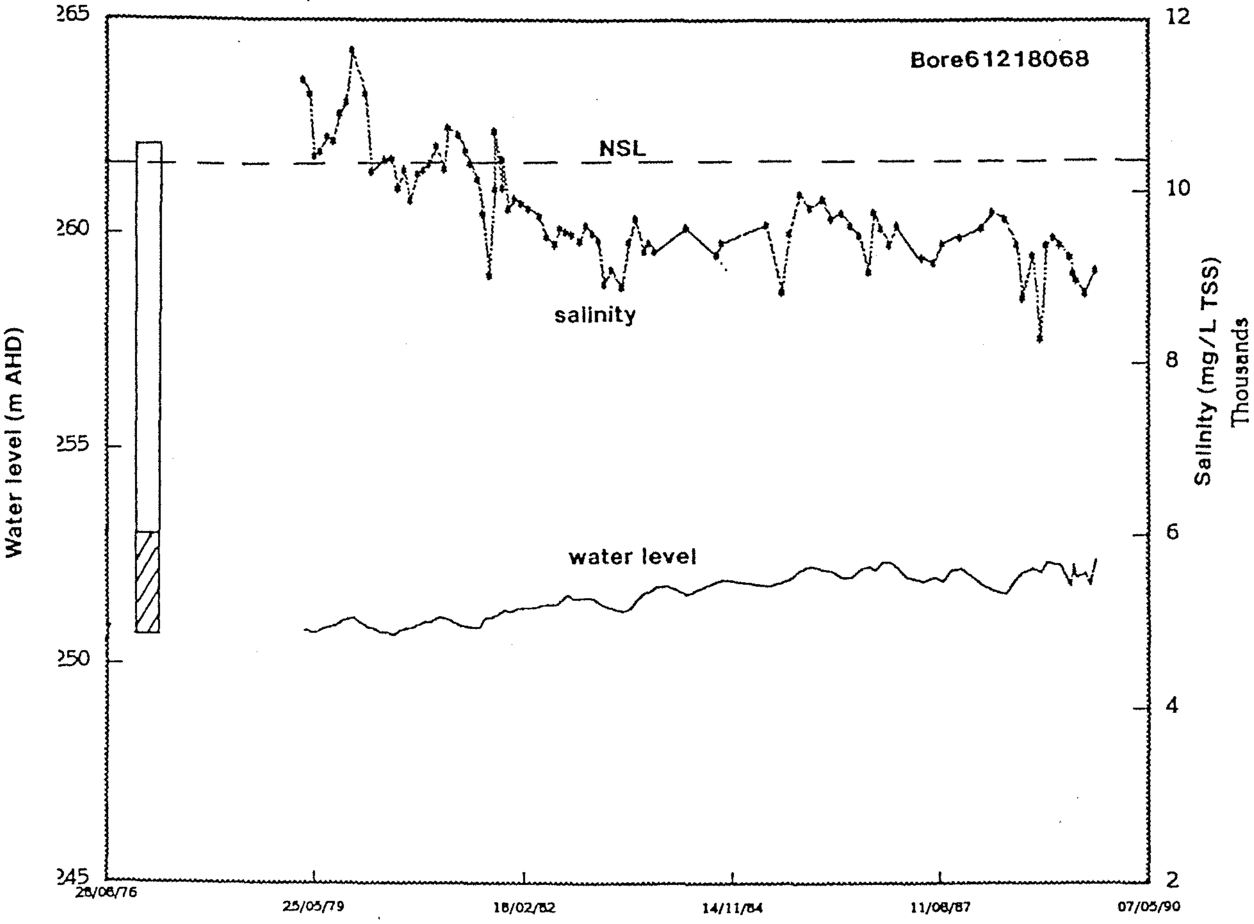

Bore61218059
NSL
water level
salinity
Water level (m AHD)
Salinity (mg/L TSS)
Thousands
270
265
260
255
250
10
8
6
4
2
0
28/08/76
25/05/79
18/02/82
14/11/84
11/08/87
07/05/90


Bore61218062
NSL
water level
salinity
Water level (m AHD)
Salinity (mg/L TSS)
Thousands
270
265
260
255
250
10
8
6
4
2
0
28/08/76
25/05/79
18/02/82
14/11/84
11/08/87
07/05/90


Bore61218067
NSL
water level
salinity
Water level (m AHD)
Salinity (mg/L TSS)
Thousands
270
265
260
255
250
10
8
6
4
2
0
28/08/76
25/05/79
18/02/82
14/11/84
11/08/87
07/05/90


Bore61218051
NSL
water level
salinity
Watel level (m AHD)
Salinity (mg/L TSS)
Thousands
280
270
260
250
240
10
8
6
4
2
0
28/08/76
25/05/79
18/02/82
14/11/84
11/08/87
07/05/90


Bore61218054
NSL
salinity
water level
Water level (m AHD)
Salinity (mg/L TSS)
Thousands
265
260
255
250
245
10
8
6
4
2
0
28/08/76
25/05/79
18/02/82
14/11/84
11/08/87
07/05/90


Bore61218068
NSL
salinity
water level
Water level (m AHD)
Salinity (mg/L TSS) Thousands
265
260
255
250
245
12
10
8
6
4
2
28/08/76
25/05/79
18/02/82
14/11/84
11/08/87
07/05/90