GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

RECORD 1987/6

REVIEW OF THE EFFECT OF LOGGING ON GROUNDWATER IN THE SOUTHERN FOREST OF WESTERN AUSTRALIA -PROJECT 2, PAIRED CATCHMENT STUDY

by
M.W. Martin

DEPARTMENT OF MINES
WESTERN AUSTRALIA

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This report has been prepared for the Forest Management
Subcomittee of the Research Steering Committee.

PERTH, 1986

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ABSTRACT

Hydrogeological investigations in experimental catchments in the southern forest of Western Australia have shown that logging has resulted in a rise in groundwater levels. In the three to four years since logging, groundwater levels have stopped rising or the rate of rise has decreased. However the period of regeneration is too short to predict the time required for the groundwater levels to approach pre-logging conditions. Retention of vegetation in stream areas appears to limit the rise in groundwater levels, but further monitoring is required to determine if the retained vegetation can transpire additional groundwater which may flow from the logged areas during the regeneration period.

The results indicate that the rising groundwater dissolved salt which was stored in the unsaturated zone, and that there is an increase in groundwater salinity near the water table. Groundwater did not discharge to the streams in the low rainfall (average rainfall less than 900 mm yr^{-1}) catchments. In the catchments where groundwater discharges to the streams, the maximum stream salinities after logging were much less than the groundwater salinity, which indicates dilution by surface and shallow subsurface flow. The effect of logging on groundwater and stream salinity was greatest in the intermediate rainfall zone (average rainfall 900-1100 mm yr^{-1}) where groundwater discharges to the streams and soil salt storage is high.

Logging has occurred during a period of below average rainfall, and the prevailing climatic conditions during logging operations must be considered when assessing the impact which the logging may have on stream salinities. The control catchments, particularly the lower rainfall Yerraminnup North catchment, should be retained in their

natural state and monitoring continued to provide information on variations in groundwater levels over a greater range of rainfall conditions.

INTRODUCTION

Project 2, a paired catchment study, was established in 1975 by the Steering Committee on Research into the Effects of the Woodchip Industry on Water Resources in south Western Australia within the wood chipping licence area. This area covers 9 000 km^2 of the lower southwest of Western Australia (Fig. 1), and contains the catchment areas of some of the state's major "freshwater" rivers, including the Warren, Donnelly, Shannon, and Deep Rivers.

There is a range of climatic, vegetation, and hydrological conditions within the woodchip licence area. Seven catchments, comprising two pairs, Yerraminnup Creek and Lewin; and one group of three, April Road North and South, and March Road (Sutton block), were selected to represent this range. The main features of the catchments have been presented in an earlier review (West Australia Department of Conservation and Environment 1980).

The woodchip licence area has been classified into three broad zones which are referred to as : the low rainfall zone, where average annual rainfall is less than 900 mm; the intermediate rainfall zone, with average annual rainfall between 900 and 1200 mm; and the high rainfall zone, which covers the area where average annual rainfall exceeds 1200 mm.

The Environmental Impact Statement for the woodchip project (Forests Dept, 1973) recognized that, under

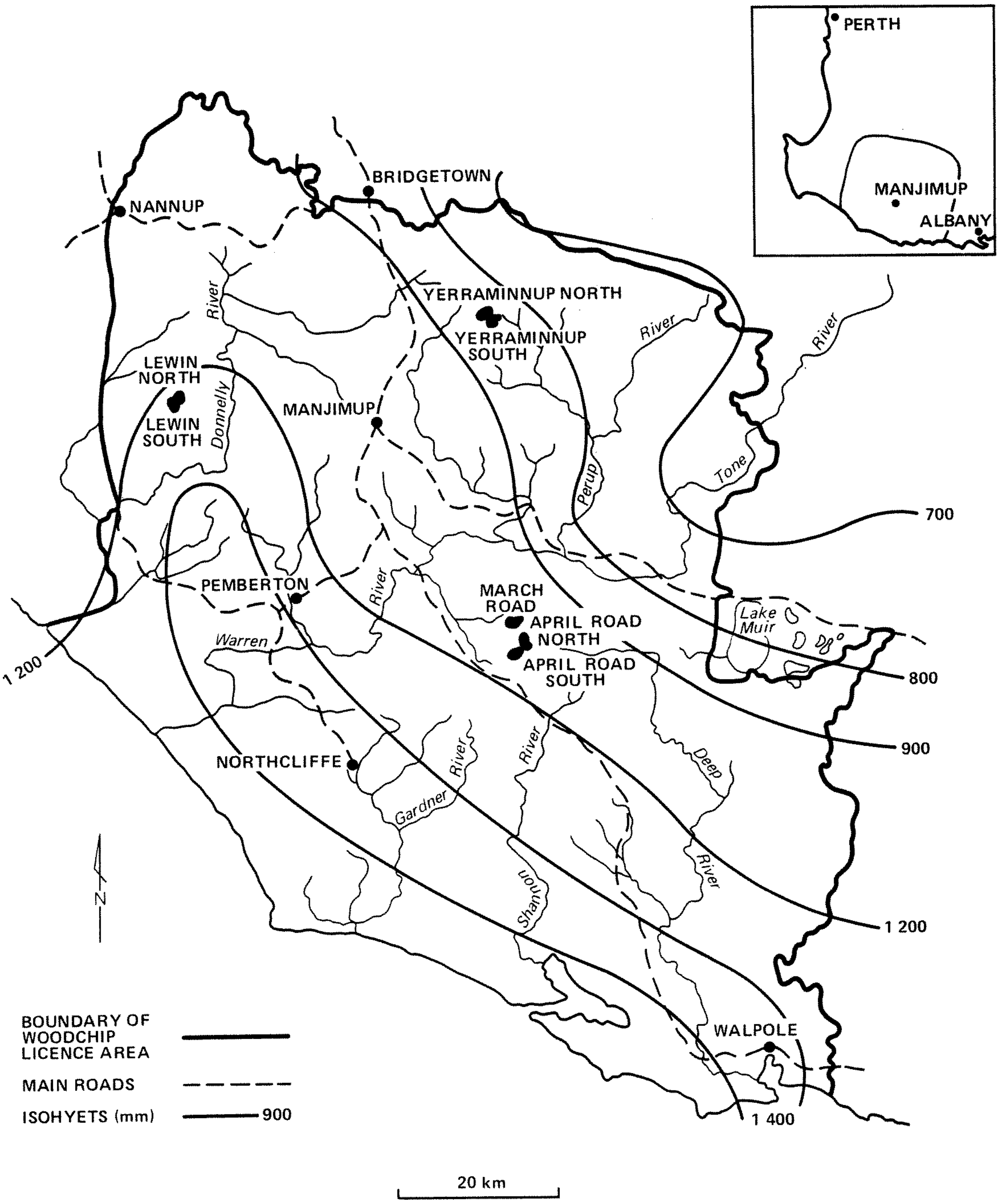


Figure 1 Location of the Project 2 experimental catchment

certain conditions, cutting of timber may result in a salinity problem, particularly in the drier, salt-sensitive, northeastern sector. Provision was made to avoid logging that sector, pending the results of the first decade of research.

Project 2 is a long-term study which involves monitoring of surface and underground water in paired catchments. One catchment in each group has been retained as a pristine control whilst the others were logged. The purpose of the study is to provide quantitative information on changes in the water and salt balances of the catchments that resulted from forest operations associated with the woodchip industry. The project is primarily concerned with changes in water quality, particularly salinity levels and turbidity of surface run-off.

This report is a hydrogeological evaluation of the groundwater-monitoring data for the period 1976 to 1985, with particular reference to the early response of groundwater levels and salinity since the logging and regeneration treatments in 1982/83.

GEOLOGY

REGIONAL SETTING

The area is predominantly underlain by Precambrian granites, migmatites, and metamorphic rocks of the southwest Yilgarn Block and Albany-Frazer Province (Wilde and others, 1984). The basement rocks have been variably weathered and lateritized to a saprolite of multicoloured to pale leached material which consists of various proportions of silt-, clay-, and sand-sized particles. Weathering and lateritization is largely an in-situ process, and textures and structures of the original rocks may be preserved within the saprolite.

The transition from saprolite to moderately weathered and fresh rock is delineated by the limit of auger penetration. The saprolite is generally 5 m to 20 m thick and rarely exceeds 30 m, and the contact between saprolite and basement rock is usually sharp.

Much of the area is mantled by Cainozoic deposits which include laterite, alluvium, and colluvium. Laterite ranges from massive or cemented pisolites to loose, uncemented pisolites, which in southern areas may be represented by a red ferruginous soil unit. Alluvial deposits consist of conglomerate, sands and clays, and are of variable thickness. Relationships of the various alluvial deposits have been discussed by Wilde and others (1984). Colluvial deposits are generally associated with dissection of the laterite surface.

GENERAL HYDROGEOLOGY

Groundwater occurs in the saprolite and in fractures and joints of the moderately weathered to fresh basement rocks. During the winter months, or after periods of heavy rainfall, perched groundwater occurs in the coarser surficial deposits. Groundwater recharge is by infiltration from rainfall, and discharge is by evapotranspiration and, in some cases, direct discharge to the intermittent streams.

In general, the depth to groundwater is greatest near the divides and decreases towards the valleys, and groundwater flow is from the divides to the valleys. Local topographic and geologic features which enhance recharge may result in a shallow depth to groundwater near divides.

Maximum groundwater levels occur in about December and minimums in April, but there is a lag in the timing of maxima and minima as the depth to water increases. There is also a decrease in the amplitude of seasonal water-level changes with increasing depth to water. The seasonal fluctuations of the water table may be attenuated in valley locations if the water table rises to the surface.

INVESTIGATION PROCEDURES

DRILLING AND BORE CONSTRUCTION

Groundwater monitoring bores were established in the catchments using auger drilling with wire-line coring. Core samples were collected for lithological description and soil-salt analyses.

Soil salinity results have been reported by Johnston and others (1980), and lithological descriptions of cores are held by Geological Survey of Western Australia.

Observation bores were constructed using PVC casing which was slotted from 2 m below ground surface to the base of the hole. The bores were gravel packed over the slotted interval, and the remaining annulus was sealed with cement. Review of the data in 1979 indicated that the cement seal had failed in some bores, and water from the surface or perching layers was leaking into the casing. Some of these bores were replaced as part of a drilling programme in 1981.

At sites where the hydraulic head increases with depth the fully slotted observation bores are monitoring a potentiometric head rather than the water table. As the major effect of logging on the surface-water quality was likely to arise from groundwater discharge to streams, additional bores were established at some sites during the 1981 programme. These bores were constructed with a short (1 to 2 m) slotted interval, positioned near or above the maximum recorded water level. Bores were also established at some sites to monitor the shallow, perched groundwater system.

TREATMENT OF CATCHMENTS

After a six-year calibration period (1976-1981), one catchment in each group was retained to provide base-level data for the undisturbed response and a control for determining the effect of the subsequent logging in the remaining catchments. A summary of catchment treatment is shown in Table 1.

Road works and drainages were constructed in 1981, logging commenced in early 1982, and regeneration burns were completed by the 1983/84 summer.

A 200 m wide corridor along the main valley up to the catchment divide was not logged on the April Road North catchment, and a 100 m wide 'stream buffer' was retained along all water courses in the Yerraminnup South catchment.

TABLE 1. LOGGING HISTORY

	Roadings month/yr	Logged month/yr	Regeneration Burn month/yr	Stream Buffer (m)
Yerraminnup South	10-11/81	1/82-4/83	10/83	100
April Road North	4-5/81	1/82-6/82 9/82-3/83	3/83	200
March Road	4-5/81	1/82-3/83	3/83	-
Lewin South	3/81	1/82-12/82	11/83 2/84	-

GROUNDWATER MONITORING

Groundwater levels and salinity have been monitored by the Water Authority of Western Australia (previously Public Works Department) at monthly intervals since 1976. The record is not complete for some bores, with breaks in the record of several months in some instances.

Groundwater hydrographs from bores in the logged and control catchments were compared, and those with a similar response during the calibration period were selected for post-logging comparisons. The effect of the logging operation was determined from the difference in seasonal minimum groundwater levels between the control- and logged-catchment hydrographs after correction for elevation differences (Fig. 2). The change in water level was determined from the average change in the seasonal minimum water level from 1981 to 1985 for bores in each logged catchment, and compared with the average change in water levels for the control catchments over the same period (Fig. 2).

Synoptic water-level contour maps for the 1981 (pre-logging) and 1985 (post-logging) seasonal minimum were prepared and used to produce depth-to-water maps for the logged catchments.

Changes in groundwater salinity have been estimated by comparing pre-logging groundwater salinity with soil-solute concentrations in the zone over which groundwater has risen.

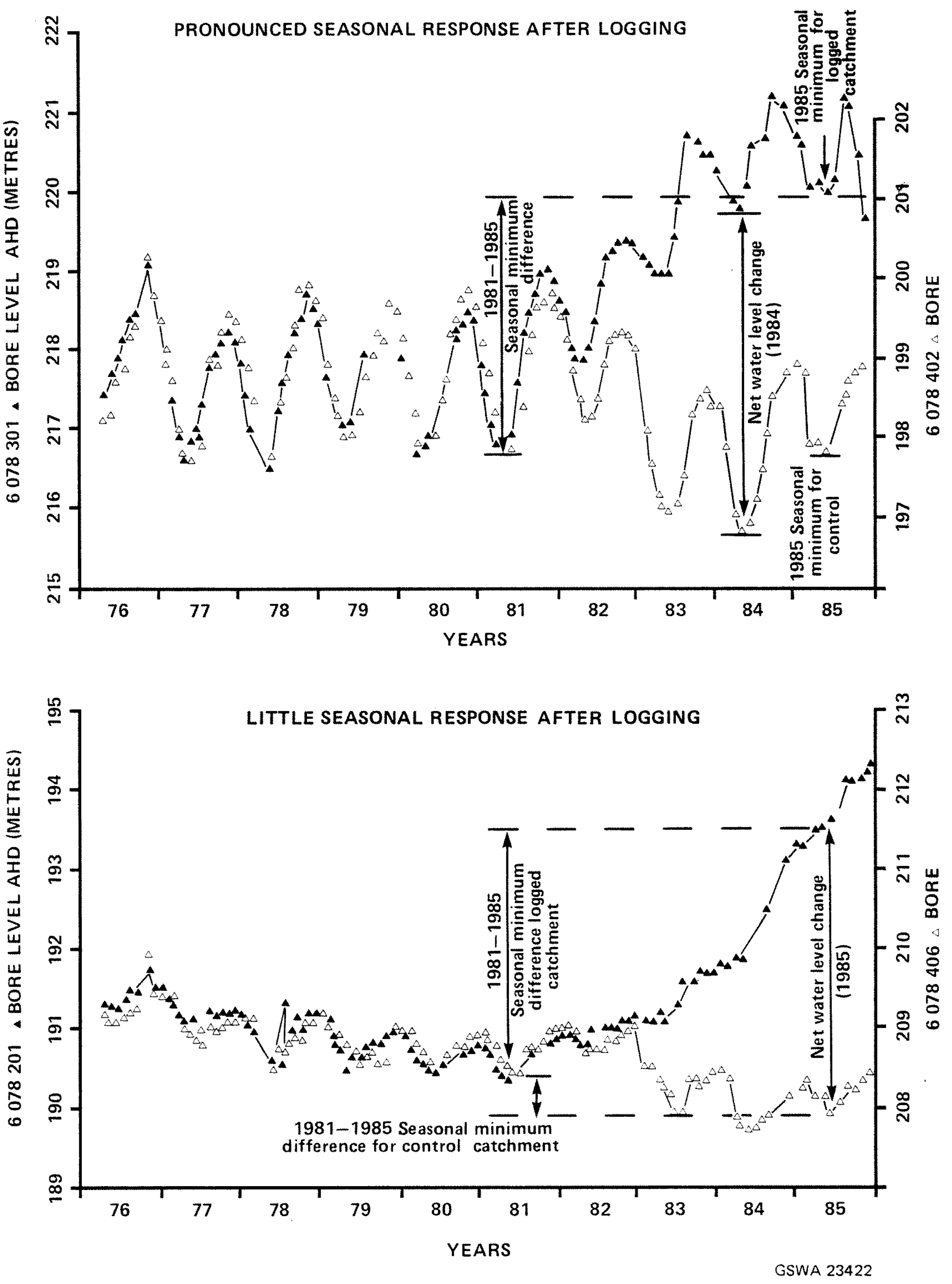


Figure 2 Determination of net water-level change and seasonal minimum difference after logging

LIMITATIONS ON DATA INTERPRETATION

Interpretation of the effect of logging on groundwater is constrained by a number of factors:

1. The small number of observation points on each catchment restricts the accuracy of the water-level contour maps. This also applies to other data generated from the water-level maps, such as depth-to-water maps.

2. Many observation bores are constructed with a slotted interval from 2 m below ground level to the base of the hole, and may be measuring the pressure at some depth in the saturated interval rather than the position of the water table. This was addressed to some degree in the 1981 drilling, but only at a few sites.

3. Groundwater samples which are collected from bores that are slotted over the full saturated interval may not reflect changes in groundwater salinity which are occurring at the water table, particularly if samples are taken from the base of the bore.

4. There are only a few bore-hydrographs from each logged catchment which have a comparable control.

5. The post-logging period of about three years is too short to idicate the full effect of logging and regeneration.

EFFECT OF LOGGING ON GROUNDWATER LEVELS

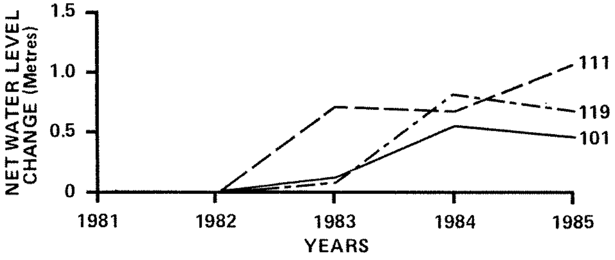
The net change in groundwater level after logging is defined as the difference between the predicted groundwater level had logging not occurred and the observed groundwater level after logging. To determine this the groundwater hydrograph from a bore in the control catchment, which had a similar response to a bore in the logged catchment during the pre-logging period, is used to determine the predicted groundwater level.

The peaks of the groundwater hydrographs are strongly influenced by annual rainfall. In order to minimize this effect, the net change in groundwater level has been calculated at the time of the seasonal minimum. Where there is a pronounced seasonal fluctuation in the observed water levels after logging, the net change is the difference between observed and predicted minimum value for each year. The difference at the time of predicted seasonal minimum is used if the response of the logged-catchment hydrograph has little seasonal variation. This is illustrated on Figure 2, and the net changes are shown on Table 2 and Figure 3. The net change in groundwater level can not be calculated for all bores in the logged catchments because of the limited number of suitable control hydrographs.

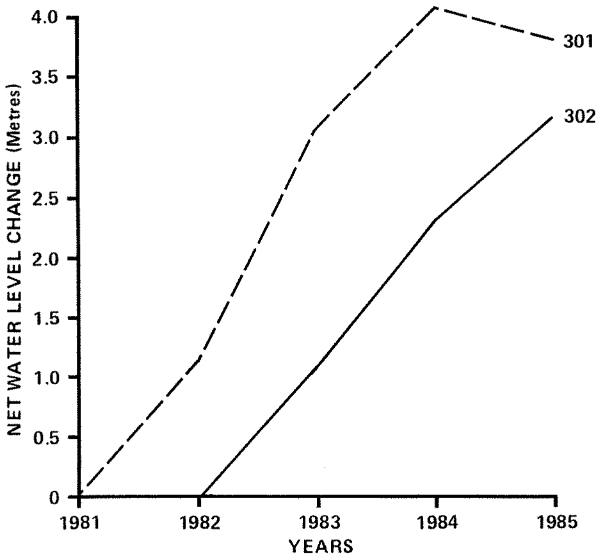
TABLE 2. NET WATER-LEVEL CHANGE OF LOGGED CATCHMENTS

Bore No.* **(Logged/control)**	**Rise (metres)** 1981	 1982	 1983	 1984	 1985
Yerraminnup Creek South					
111/013	-	-	0.72	0.68	1.08
101/017	-	-	0.14	0.56	0.48
119/016	-	-	0.12	0.84	0.68
March Road					
201/406	-	0.24	1.32	2.24	3.48
202/402	0.16	0.80	3.20	3.72	3.20
210/405	-	0.64	0.76	1.52	1.80
April Road North					
301/402	-	1.16	3.08	4.08	3.30
302/406	-	-	1.08	2.32	3.16
Lewin South					
106/012	0.64	1.60	1.80	2.76	2.24
108/001	0.44	1.12	2.20	3.56	3.56
102/013	0.88	1.92	2.92	3.32	3.52

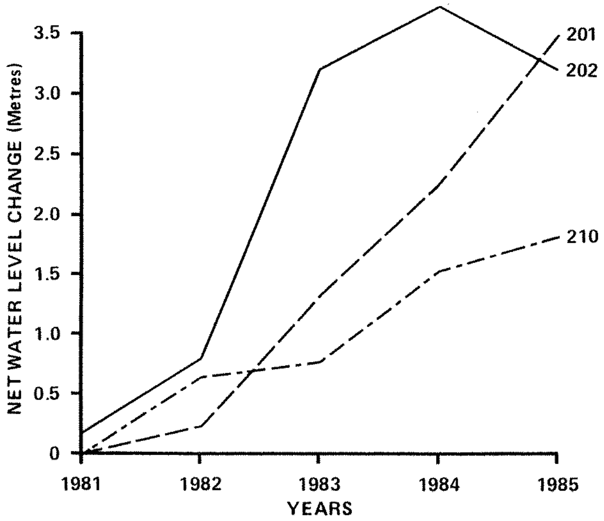
* Bores are identified by an eight digit numbering system, however only the last 3 digits are used in the text, details are contained in the introduction to Appendix A.



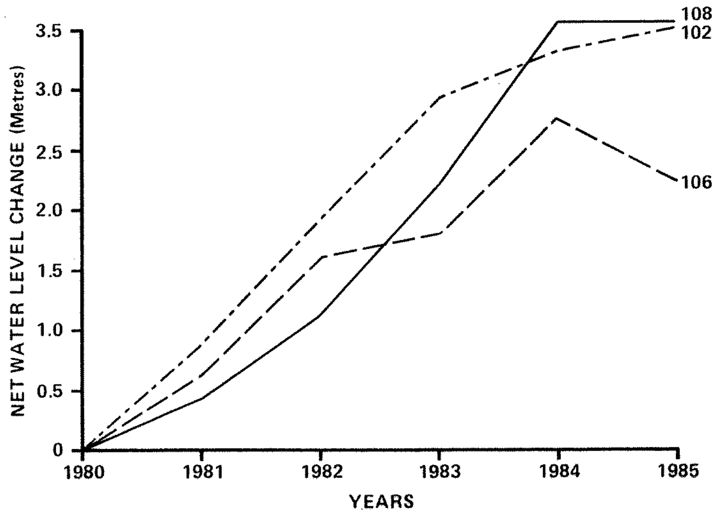
YERRAMINNUP CREEK SOUTH



APRIL ROAD NORTH



MARCH ROAD



LEWIN SOUTH

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Figure 3 Net water-level change of all catchments

The average water-level change at each catchment from the 1981 to 1985 seasonal minimum is presented in Table 3.

TABLE 3. AVERAGE WATER-LEVEL CHANGE OF ALL CATCHMENTS

	1981 to 1985 SEASONAL MINIMUM LEVELS				
	No. of bores	**Maximum (m)**	**Minimum (m)**	**Mean (m)**	**Std dev.**
Yerraminnup South (Logged)	9	1.1	0.14	0.72	0.31
Yerraminnup North (Control)	13	0.19	-0.60	-0.05	0.22
March Road (Logged)	6	3.43	1.78	2.81	0.56
April Road North (Logged)	10	4.02	0.34	2.51	1.36
April Road South (Control)	6	0	-0.51	-0.26	0.17
Lewin South (Logged)	8	3.01	1.39	2.31	0.61
Lewin North (Control)	12	0	-0.45	-0.20	0.13

Stream reserves were retained on the Yerraminnup South and April Road North catchments, and the average water-level changes for stream reserve bores and bores in the logged areas of the catchments are given in Table 4.

TABLE 4. AVERAGE WATER LEVEL CHANGE, 1981 TO 1985 SEASONAL MINIMUM LEVELS FOR LOGGED AND STREAM RESERVE AREAS

	Logged catchment			Stream reserve		
	No. bores	Mean (m)	Std dev.	No. bores	Mean (m)	Std dev.
Yerraminnup South	6	0.85	0.23	3	0.45	0.30
April Road North	6	3.53	0.32	4	0.99	0.47

The average annual rainfall for all catchments from 1976 to 1985 has been less than the long-term average (Table 5). The rise in groundwater level may be greater during periods of higher annual rainfall. This must be considered when using the results of this study to predict the catchment response to logging.

TABLE 5. ANNUAL RAINFALL OF ALL CATCHMENTS

	Yerraminnup Creek		April Road		March Road	Lewin	
	North	South	North	South		North	South
			(mm)				
1976	780	786	1010	1040	988	1130	1131
1977	707	701	994	997	974	1069	1046
1978	883	851	1094	1117	1055	1125	1137
1979	690	666	932	935	932	1077	1069
1980	768	729	992	982	929	1165	1148
1981	851	829	1158	1178	1121	1181	1166
1982	628	607	827	826	807	941	936
1983	831	816	898	940	922	1137	1131
1984	780	802	1129	1146	1114	1184	1198
1985	722	716	914	951	927	1007	1015
10 year mean	766	750	995	1011	977	1102	1098
Long term mean	850		1070			1220	

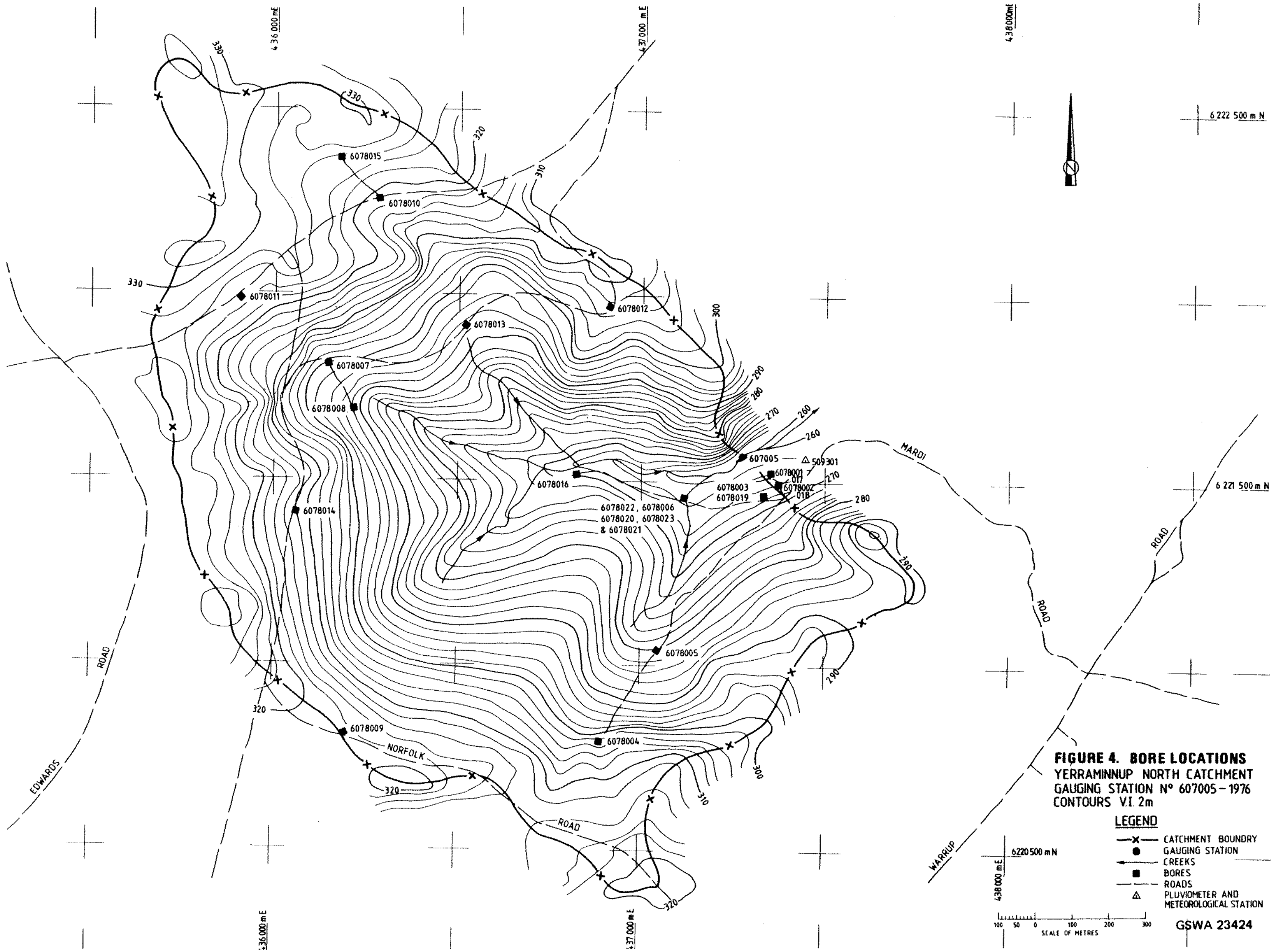

FIGURE 4. BORE LOCATIONS
YERRAMINNUP NORTH CATCHMENT
GAUGING STATION N° 607005 – 1976
CONTOURS V.I. 2m

YERRAMINNUP CREEK SOUTH CATCHMENT

Bore locations in the Yerraminnup Creek North and South catchments are shown on Figures 4 and 5. Basement topography, groundwater level, saturated thickness, and depth to water for Yerraminnup South are shown on Figures 21-25 (Appendix).

Water-level response

The average rise in groundwater level from 1981 to 1985 at the Yerraminnup South catchment is 0.72 m (Table 3). In general, the greater rise occurred in the lower valley area, however the average rise for bores in the stream buffer (Table 4) is less than the catchment average, which reflects greater interception and transpiration by vegetation from this area.

For the control catchment, there has been an average decline of 0.05 m during the post-logging period with a random spatial distribution in water-level rise and decline.

There is insufficient data to determine water-level trends during the post-logging period. While some bore hydrographs indicate a decrease in the rate of rise, there has not been a decline in seasonal minimum water levels at any bore.

Net water-level change

The bores at the Yerraminnup Creek South catchment for which net water-level changes can be calculated, are in the stream buffer. The net change reflects the effect of logging, and interception and transpiration by vegetation

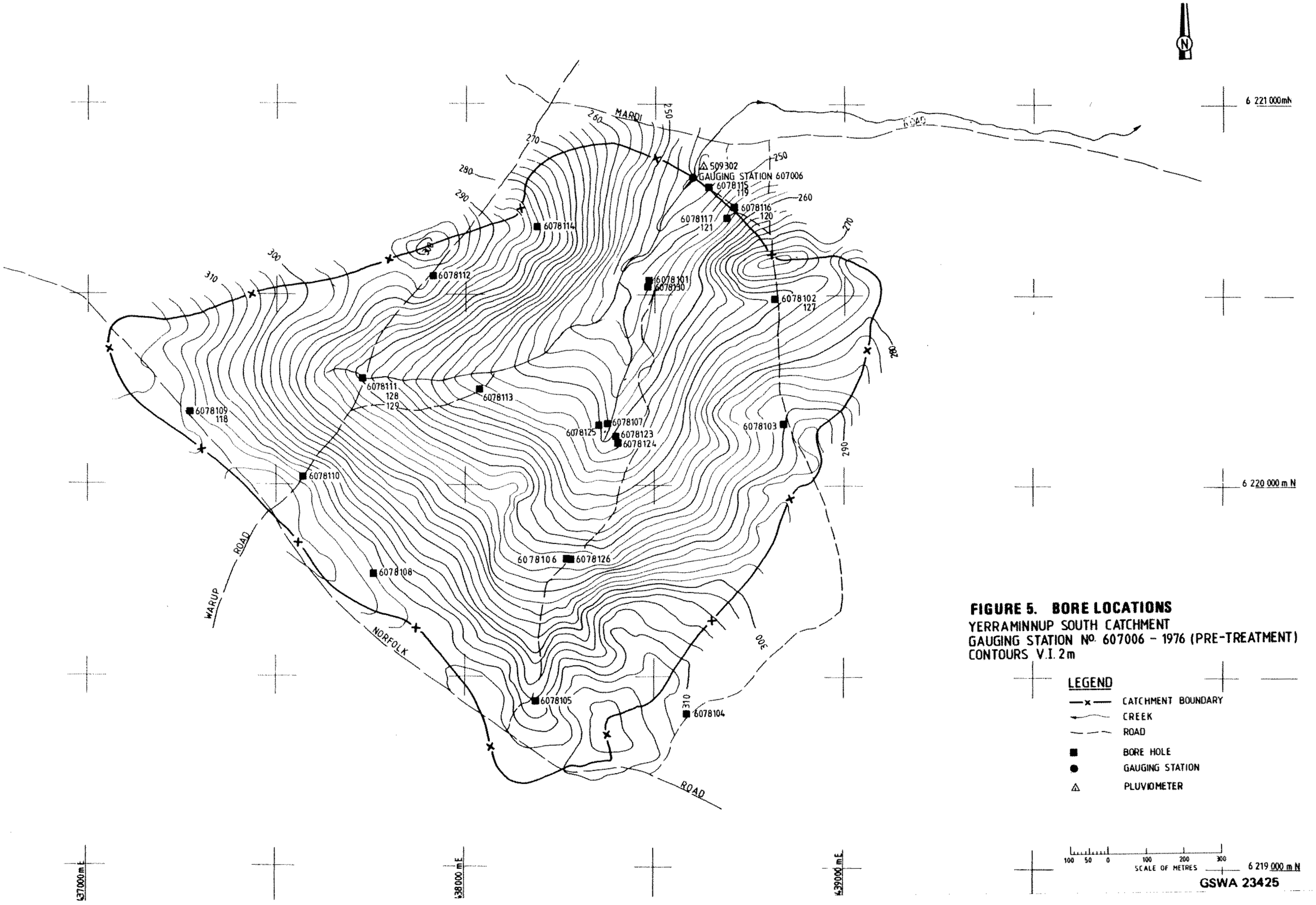

FIGURE 5. BORE LOCATIONS
YERRAMINNUP SOUTH CATCHMENT
GAUGING STATION No. 607006 - 1976 (PRE-TREATMENT)
CONTOURS V.I. 2m

GSWA 23425

in the stream buffer. The net changes for bores 101, 111, and 119 are shown in Figure 3.

The general pattern of net water-level change at the Yerraminnup South catchment appears to be increasing from 1982 to 1984, then it is relatively constant from 1984 to 1985. As there has been no reduction in minimum water level in the logged catchment, the constant net change indicates a rise in minimum level for the control bores (Fig. 6). The net water-level change may remain constant for several years, or may decline as vegetation regenerates. There is insufficient data at present to predict future trends.

Depth to water

The depth to groundwater at Yerraminnup South after logging was about 20-30 m near the catchment divide, and is less than 12 m in the valley (Fig. 25; Appendix). The shallowest depth to groundwater following logging occurred in December 1985 at bores 115 and 119, which are near the catchment outlet. The minimum depth to groundwater was 1.8 to 2 m in December 1985.

Perched groundwater

The shallow bores that monitor the perched groundwater system are located within the stream buffer zone. The results from these bores show that perched groundwater was present for at least four months of the year prior to logging. No groundwater was detected in 1982, but it was present for 4 to 6 months (June-November) in 1983 and 1984, and 2 to 3 months (September-November) in 1985 (Fig. 7). The presence of perched groundwater usually coincides with the wetter period, commencing in about June, but is

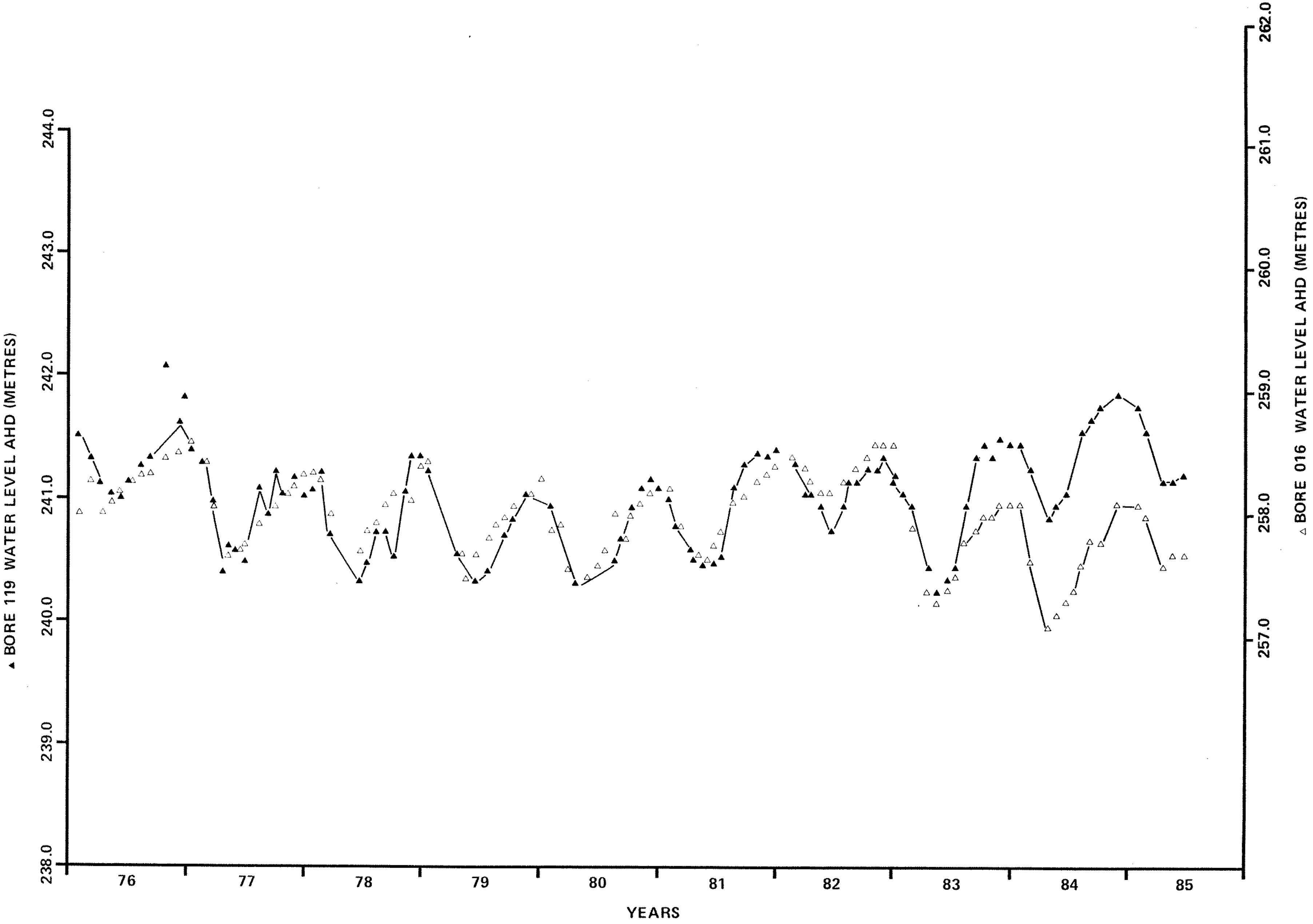

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Figure 6 Groundwater hydrographs, bores 119 and 016

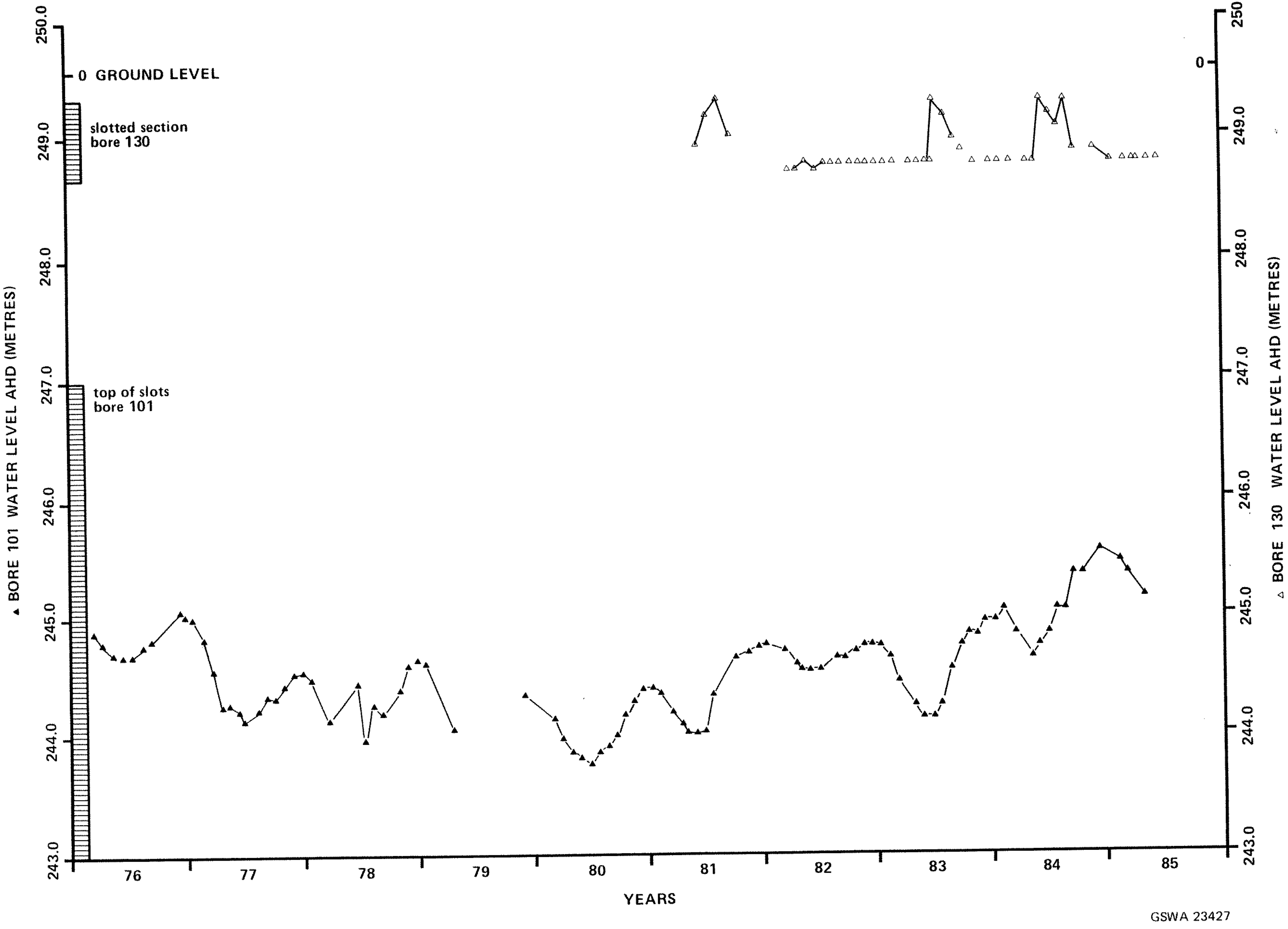

Figure 7 Perched groundwater hydrograph, Yerraminnup Creek South catchment, bores 101 and 130

influenced by the distribution of rainfall throughout the year.

Groundwater outflow

The groundwater outflow from 1975 to 1979 at the Yerraminnup South catchment was calculated by Furness (1977a) to be 350 $m^3 year^{-1}$. This was based on a hydraulic conductivity estimate of about 0.02 md^{-1} for the saturated weathered material and underlying 'permeable' bedrock. Recent work by Martin (1986) suggest that a hydraulic conductivity of 0.2 md^{-1} is not unrealistic for the weathered material. Using this figure for the weathered material and one of 0.01 md^{-1} for the bedrock component of flow (Furness 1977b), the groundwater outflow from Yerraminnup South in 1982 (Figs 22, 23, Appendix) is estimated to have been 1750 $m^3 year^{-1}$ or 0.1% of rainfall. Following logging, there was little change in the flow pattern and hydraulic gradient at the catchment outlet (Fig. 25; Appendix), but the saturated thickness increased by about 0.5 m. Outflow in 1985 was estimated to be 1900 $m^3 year^{-1}$, an increase of about 8.5% of the 1981 flow. Although groundwater outflow has increased, the figures indicate that the post-logging groundwater outflow remains a very small component (<1%)of the water balance.

APRIL ROAD NORTH CATCHMENT

The location of bores in this catchment and in April Road South, the control catchment, are shown on Figures 8 and 9.

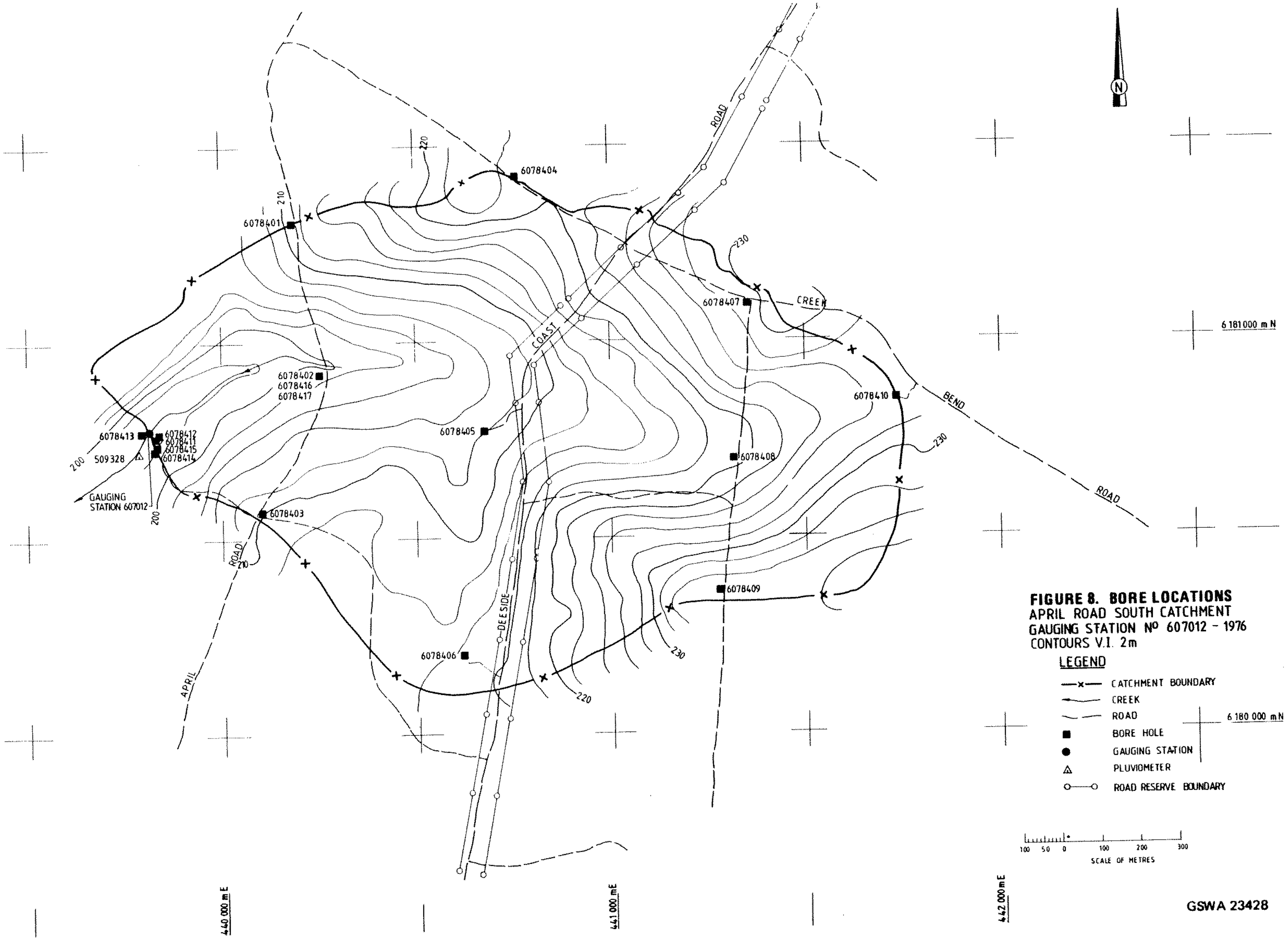

FIGURE 8. BORE LOCATIONS
APRIL ROAD SOUTH CATCHMENT
GAUGING STATION No 607012 - 1976
CONTOURS V.I. 2m

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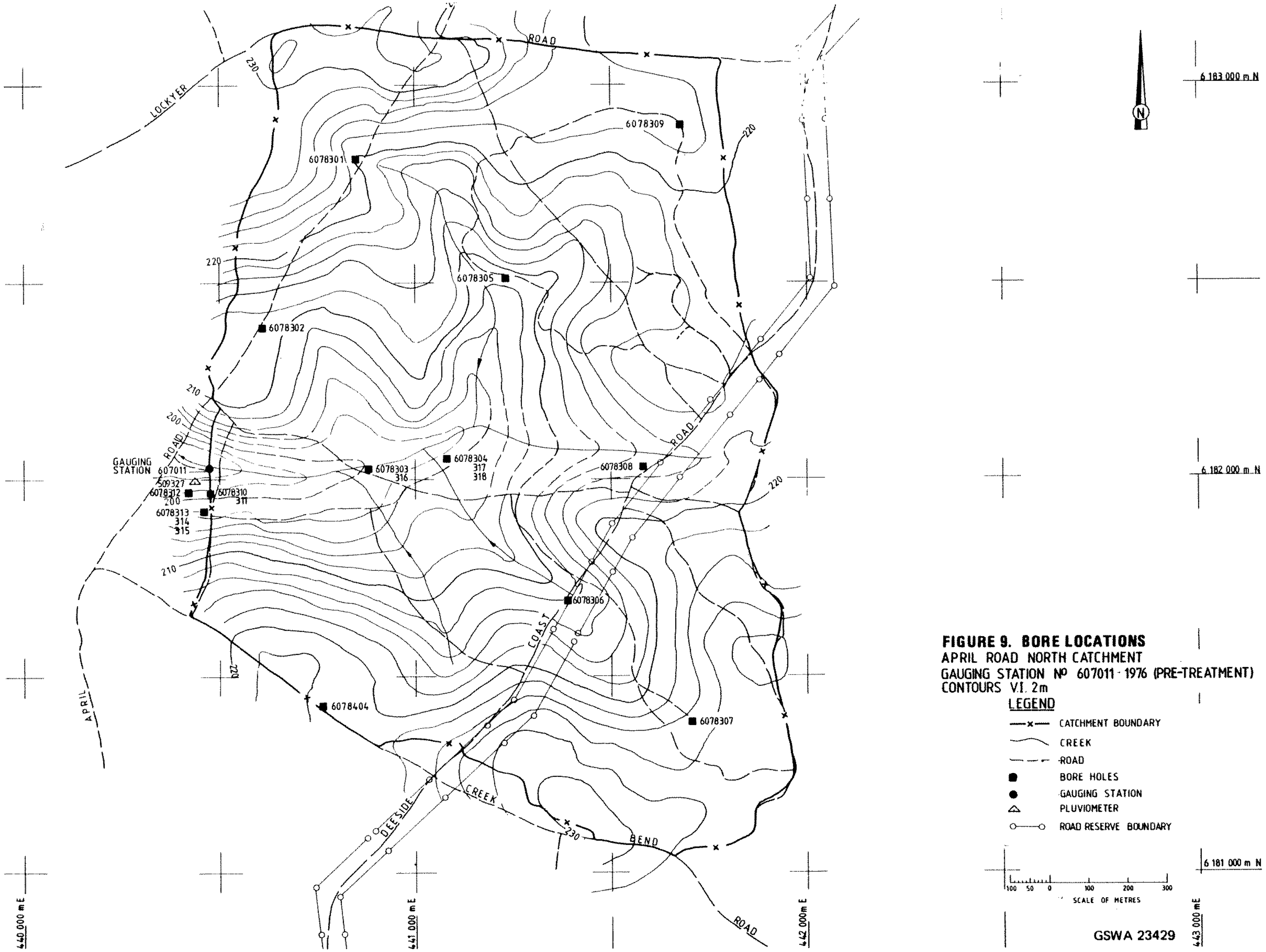

FIGURE 9. BORE LOCATIONS
APRIL ROAD NORTH CATCHMENT
GAUGING STATION № 607011 - 1976 (PRE-TREATMENT)
CONTOURS V.I. 2m

Water-level response

The average rise in seasonal minimum groundwater level from 1981 to 1985 was 2.5 m (Table 3), but was about 1 m bor bores in the stream reserve and about 3.5 m for those in the logged areas (Table 4). Seasonal minimum groundwater levels in the control catchment remained constant or declined from 1981 to 1985; the average change was a decline of 0.26 m.

In the logged areas of the catchment, there is a continuous rising trend in the seasonal minimum water levels. The rate of rise decreases from 1984 to 1985, particularly where groundwater levels are near the surface, for example, bore 301 (Fig. 10). This may indicate increased evaporation when the water table is closer to the soil surface. At bore 301, the 1983 and 1984 seasonal maximum water levels are up to 1 m above ground level, and minimums slightly below ground level. Although the water table position has not been determined at this site, it is unlikely that it will be 1 m above ground level. The hydrograph for this bore therefore reflects a potentiometric level, and water levels above ground surface after logging suggest an increasing head with depth and upward flow of groundwater.

Bores in the stream reserve show a rise in the seasonal minimum level in 1982, a fall in 1983, and a further rise in 1984 and 1985 (Fig. 11). As water levels in the control catchment had remained constant or declined, the water-level response in the stream reserve bores indicates that evapotranspiration has delayed and possibly attenuated the logging response.

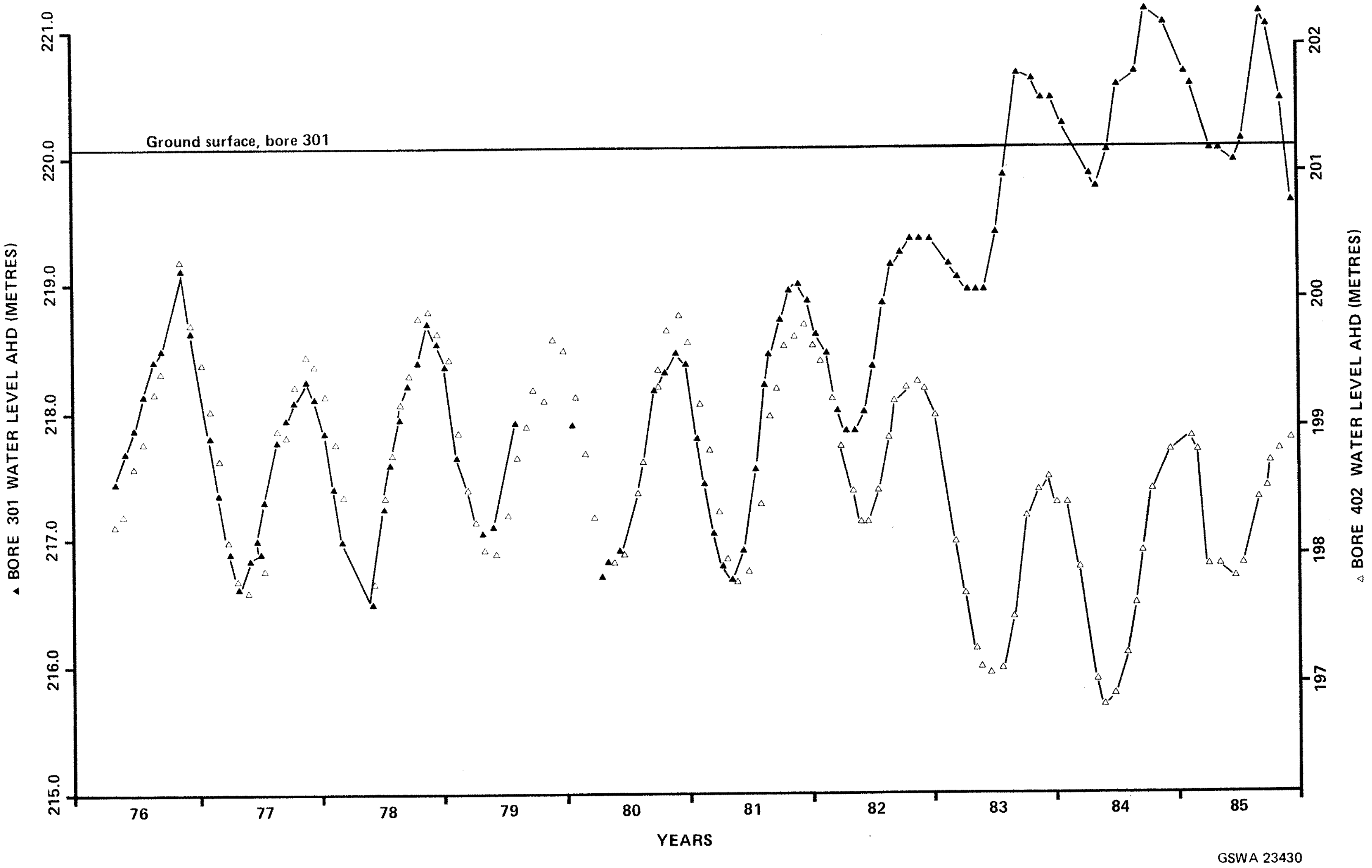

Figure 10   Groundwater hydrograph, bores 301 and 402

Net water-level change

Only two bores in the April Road North catchment, bores 301 and 302, have a similar hydrograph to bores in the control catchment.

Bore 301 is located in an upper valley swampy area where the seasonal range of water level before logging was 1 to 3 m below ground level. The net water level began to increase in 1982 at this site (Fig. 3), and reached a maximum of about 4 m by 1984. A higher seasonal minimum for the control hydrograph in 1985, and a flattening of the rising trend in the logged catchment from 1984 to 1985 (Fig. 10) resulted in a reduction in the net water-level change for 1985. The 1985 minimum water level in the logged catchment is the highest for the period of record. The lower water level for December 1985 may indicate that regenerating vegetation is beginning to lower groundwater levels.

Bore 302 is located on a slope where the depth to water before logging was about 12 m. The increase in net change was delayed until 1983 (Fig. 3), and there was a continuous increase to a maximum of 3.1 m by 1985.

Depth to Water

The depth to water at the catchment outlet before logging was about 6 m (Fig. 29; Appendix), and decreased about 0.3 m by 1985. However, for the bores in the stream reserve further up the valley (303, 304, 308), the depth to water decreased by about 1 m from 1981 to 1985 (Fig. 31; Appendix), but still remains more than 4 m below the surface. This suggests that the full effect of logging may not be observed at the catchment outlet for several more years.

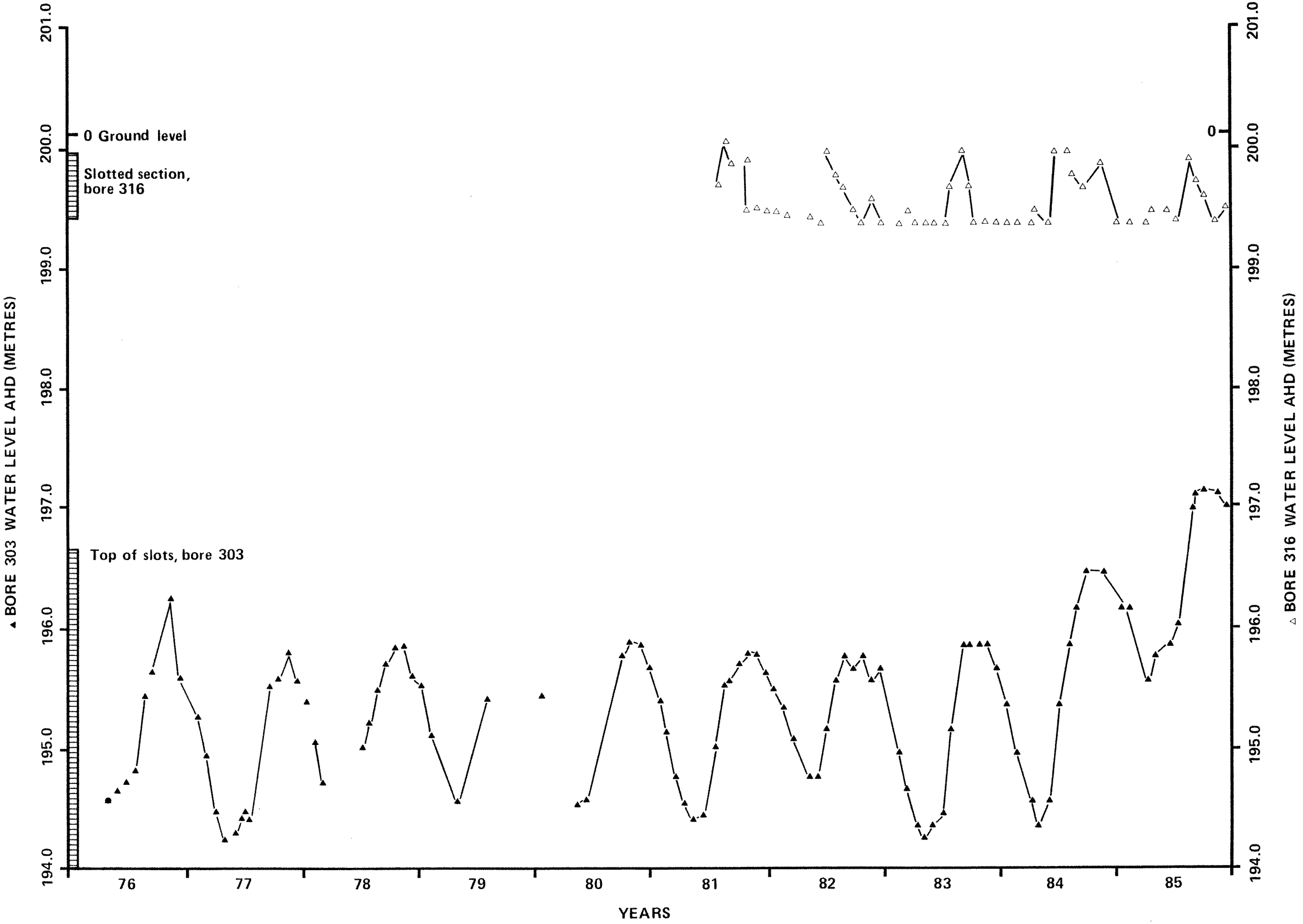

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Figure 11   Groundwater hydrographs of stream reserve bores 303 and 316

Between sites 301 and 305, and at site 306 (Fig. 9), the water levels have risen to or above the surface after logging (Fig. 31). Although there are no shallow monitoring bores at these sites, the water table probably rises to the surface for part of the year, which results in groundwater discharge to streams.

Perched Groundwater

Bores monitoring the perched aquifer are located within the stream reserve, and the monitoring results show the presence of perched groundwater prior to logging, and in all years following logging. The results from bore 316 (Fig. 11) indicate that the perched layer becomes saturated to the surface during wetter months. This may result in overland flow to the streams.

Groundwater outflow

Because of the shape of the water-level contours near the catchment outlet (Figs 27, 30; Appendix A), and the limited data in this area, it is difficult to estimate groundwater outflow from this catchment. The small rise in groundwater level at the catchment outlet after logging indicates that there has been little increase in groundwater outflow to date. However, the rise in water level in the logged area of the catchment has been greater than in the valley stream reserve (Fig. 30), and indicates increased groundwater flow to the stream reserve. The data suggest that the vegetation in the stream reserve is able to transpire the additional groundwater flow with only a small local increase in saturated storage. It may require several more years before the rise in water level in the logged area is transmitted to the stream reserve.

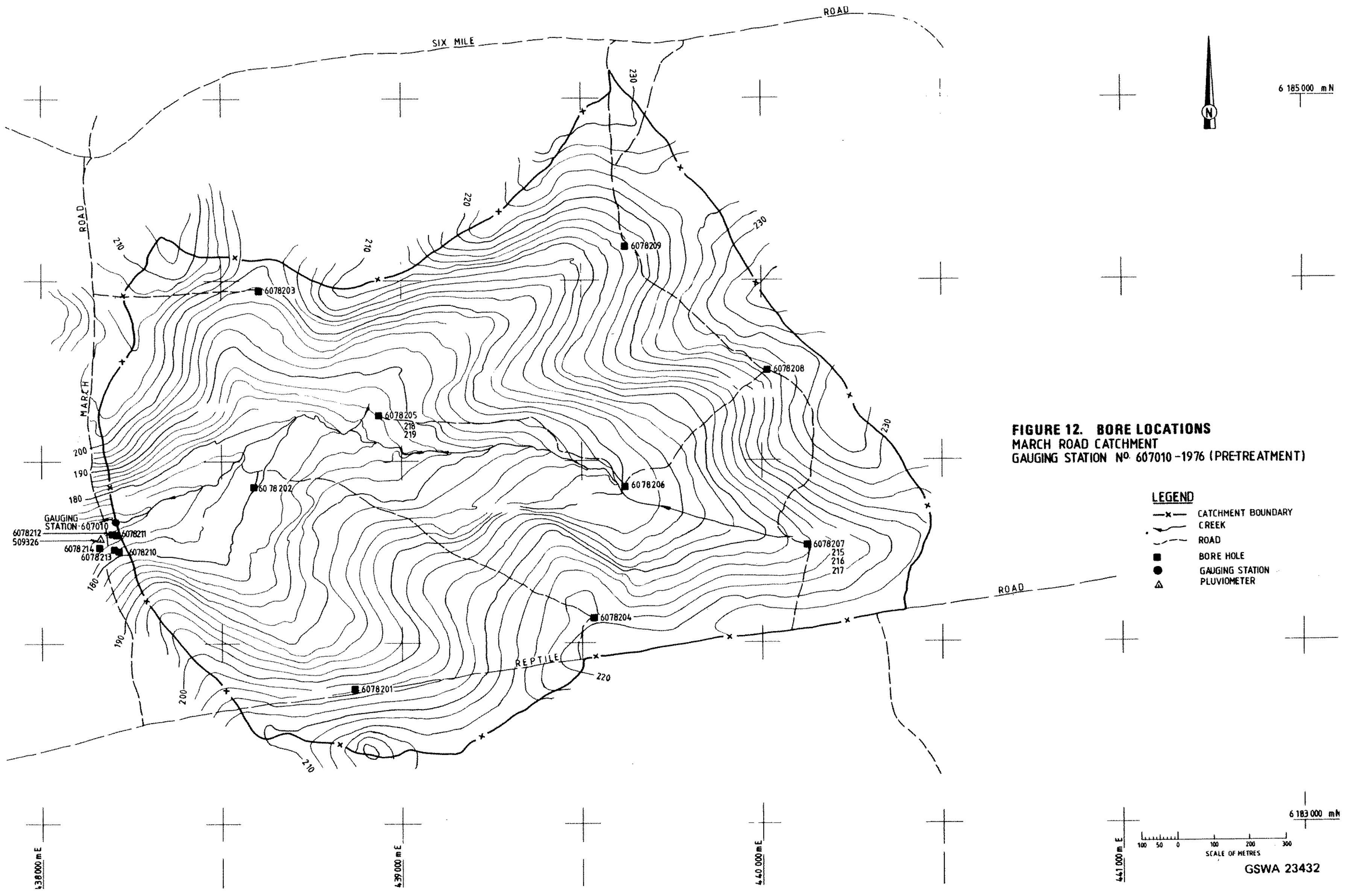
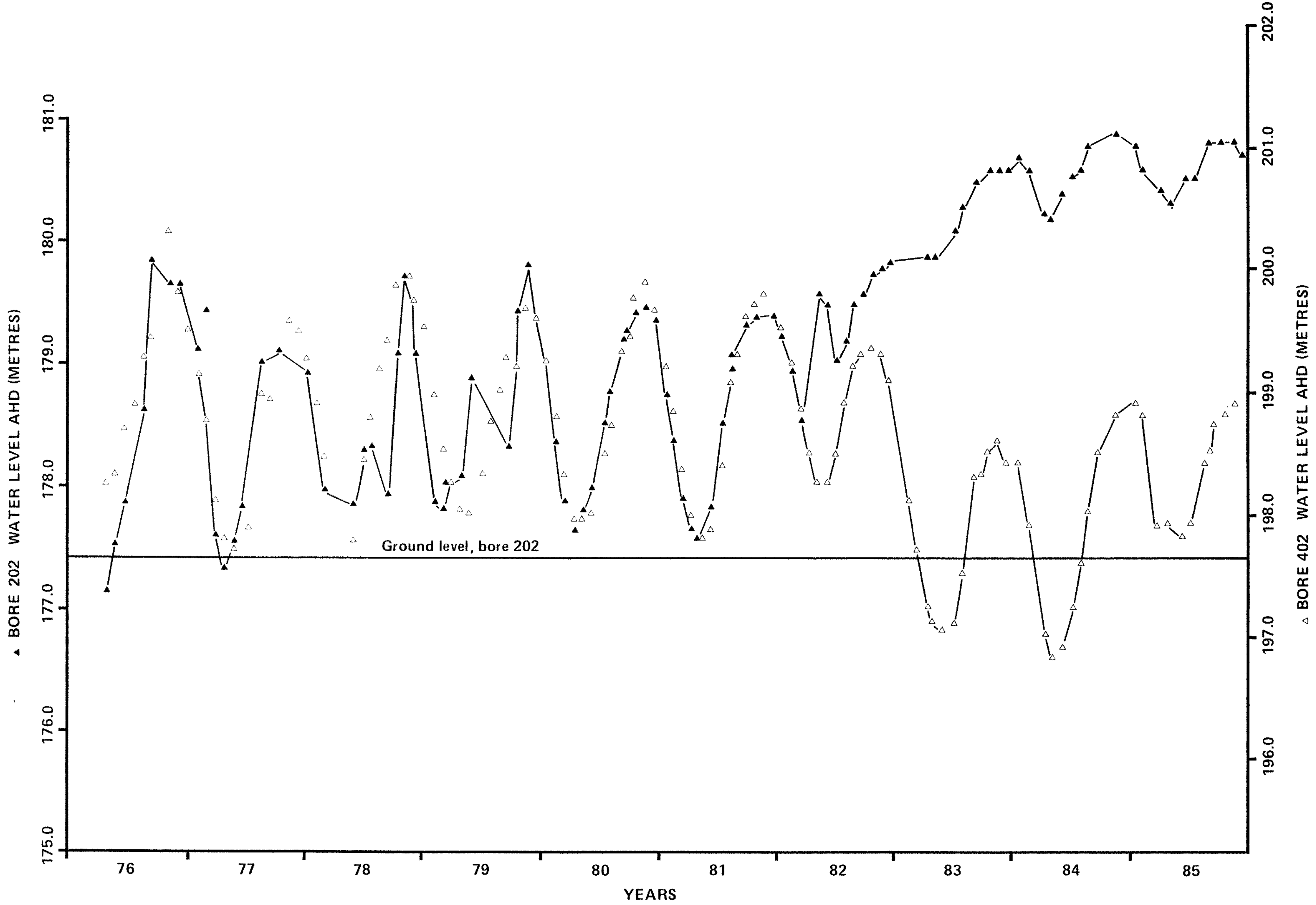


FIGURE 12. BORE LOCATIONS
MARCH ROAD CATCHMENT
GAUGING STATION Nº 607010 -1976 (PRE-TREATMENT)



GSWA 23433

Figure 13 Groundwater hydrograph, bores 202 and 402

MARCH ROAD CATCHMENT

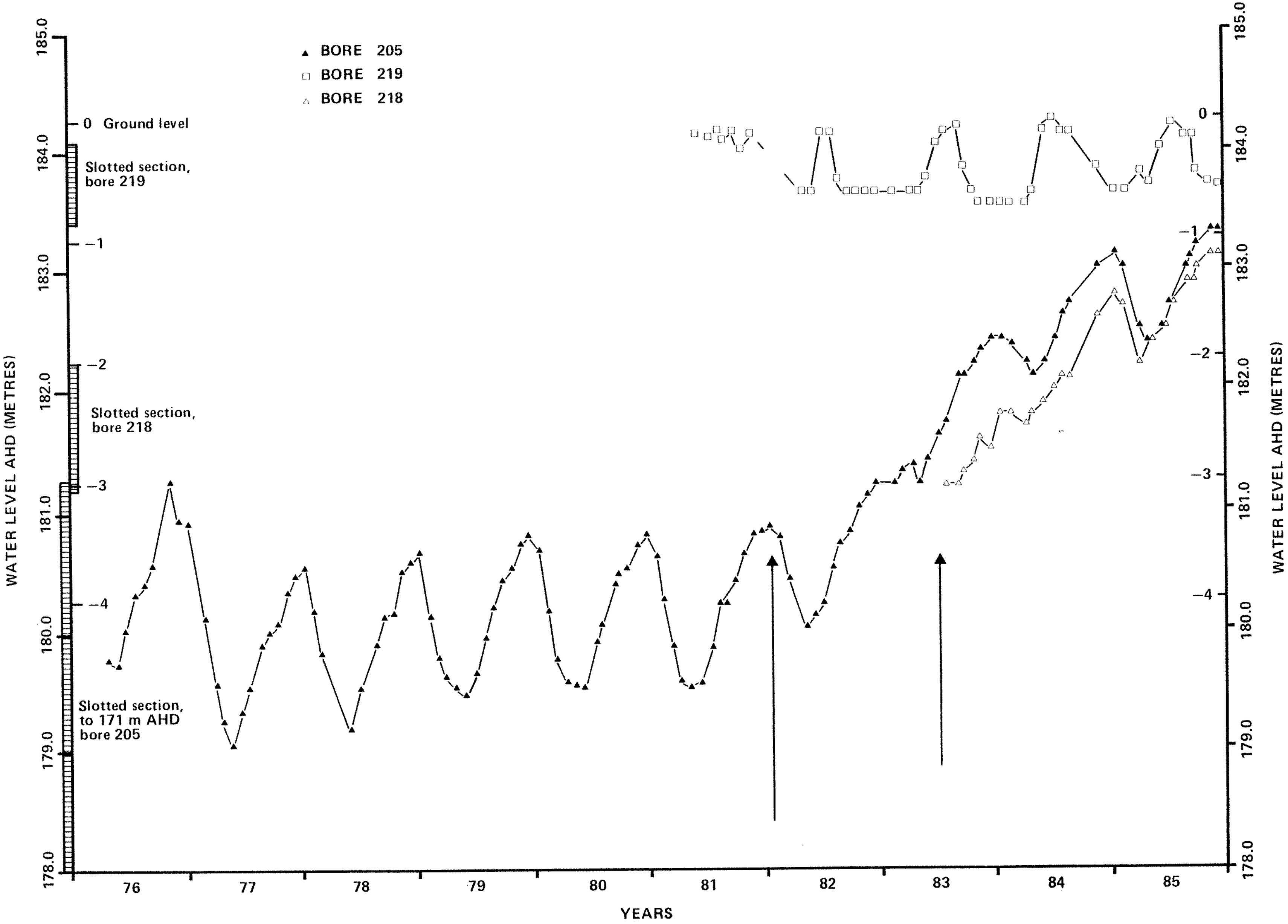
Bore locations at the March Road catchment are shown on Figure 12; April Road South catchment is the control for this catchment (Fig. 9).

Water-level response

The average rise in seasonal minimum water levels from 1981 to 1985 was 2.81 m (Table 3), but higher in the catchment, the rise was generally greater (Fig. 36). This partly reflects discharge of groundwater in the valley and the smaller saturated thickness higher in the catchment.

Water levels in the catchment show a general rising trend from 1981 to 1985. At bore 202, water levels were above ground level before logging, and surface seepage occurred during winter. Following logging, water levels rose, but the rate of rise decreased from 1983 to 1985, and there is a dampening of the seasonal water level fluctuation (Fig. 13). Although there is no water-table bore at this site, the water table has probably risen to the surface, and the height of the water level above ground level may indicate the upward head difference. The dampening of the seasonal fluctuation in water level may be due to increased evaporation from the water table and discharge of groundwater by overland and perched flow during winter.

A similar response was observed for bore 205. At this site, bore 218, adjacent to 205, is slotted over a 1.2 m interval about 1 m above the maximum pre-logging water level in bore 205. Following logging, the water table rose to within the slotted interval of bore 218 (Fig. 14), and the water table was 0.3 m to 0.5 m below the water level in 205. This head difference indicates upward flow



GSWA 23434

Figure 14 Groundwater hydrograph, bores 205, 218 and 219 of groundwater. Assuming the head difference at this site is maintained, and the water table rises to the surface, the water level in bore 205 would be 0.3-0.5 m above ground level.

Discharge of groundwater at this site, as indicated by the declining limb of the hydrograph, coincides with periods when perched groundwater is absent. By 1984, the water table is less than 2 m below the surface, and there is a flattening of the rising trend and reduced amplitude of the seasonal hydrograph. This suggests discharge by transpiration from regenerating vegetation and evaporation from the water table.

Net water-level change

The net water-level change increases from 1982 to 1984 at the March Road catchment (Fig. 3). For bores 201 (Fig.15) and 210 the increase continues for 1985, but for bore 202, the net increase is reduced in 1985. As the seasonal minimum level at 202 had not declined, the reduction in net increase reflects a rise in the seasonal minimum of the control bore. The flatter response in net water-level change for bore 210 reflects the effect of transpiration by vegetation outside the catchment boundary near this site.

Depth to water

The depth to water at the March Road catchment before logging was about 20 m on the valley flanks and decreased downslope (Fig. 35). Groundwater provided baseflow to the stream before logging, but the area where water levels are at or above ground level appears to have increased following logging (Fig. 37).

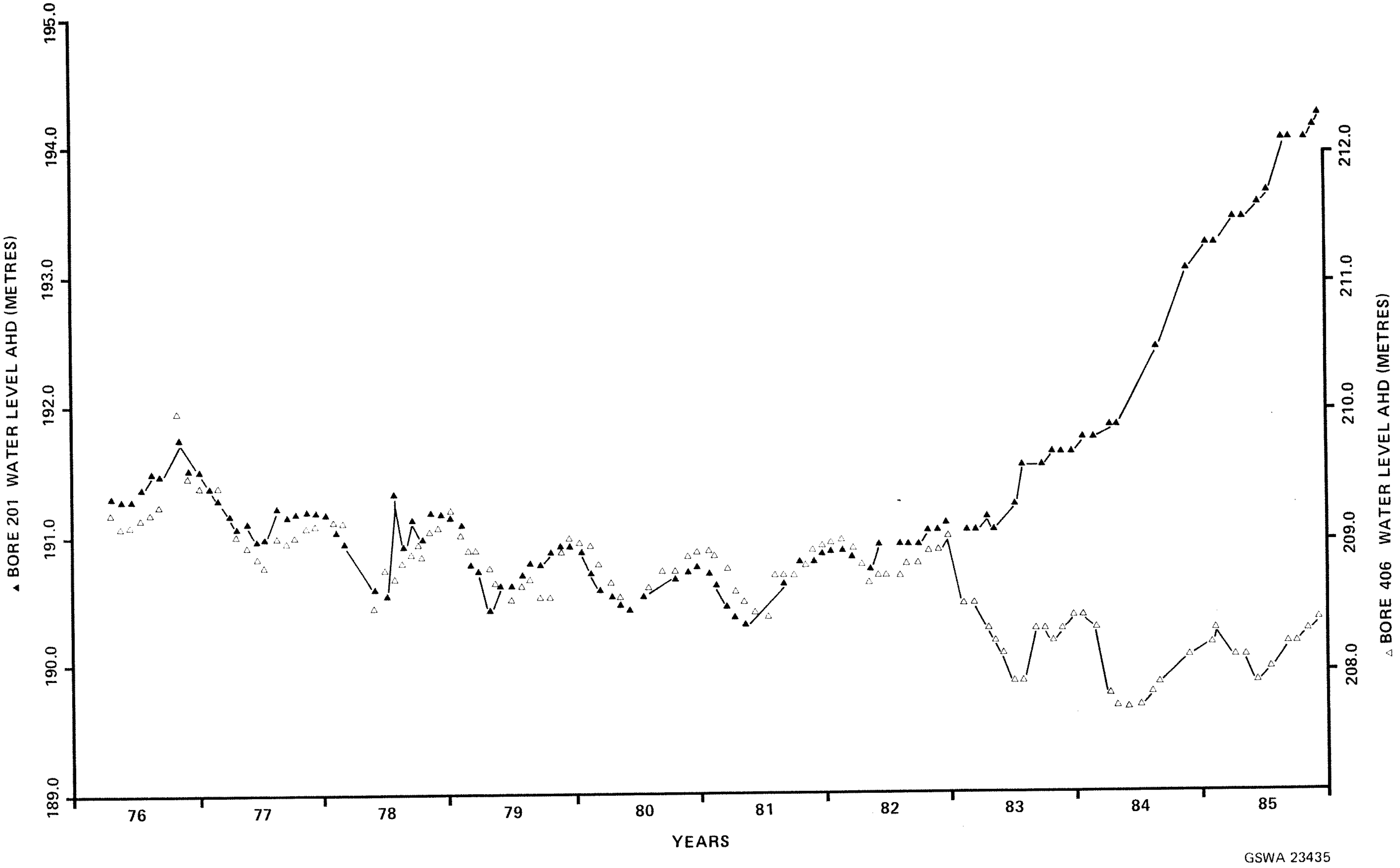


Figure 15   Groundwater hydrograph, bore 201 and 406

Perched groundwater

Perched groundwater has only been monitored at bore 219 in this catchment. The perched layer contains water for 2-6 months during wetter periods, and is probably saturated to the surface at this site for 1-2 months during winter (Fig. 14). The response of the perched system is strongly influenced by variations in rainfall.

Groundwater outflow

The rise in groundwater level following logging has resulted in an increase in saturated thickness and hydraulic gradient at the catchment outlet (Fig. 36). Groundwater outflow is estimated to have increased by 30-40% following logging.

LEWIN SOUTH CATCHMENT

Bore locations for Lewin North and South catchments are shown on Figure 16. A fuel-reduction burn was carried out at the Lewin South catchment in 1979, and both catchments were burnt in December 1981, before logging commenced. This would have affected groundwater levels before logging, but is not considered to have had a significant effect on the results from the Lewin South catchment.

Water-level response

The average rise in seasonal minimum water level from 1981 to 1985 at the Lewin South catchment was 2.3 m (Table 3), but there was a slight rise in water level following the 1979 burn. This is illustrated by the difference between the control- and logged- catchment hydrographs

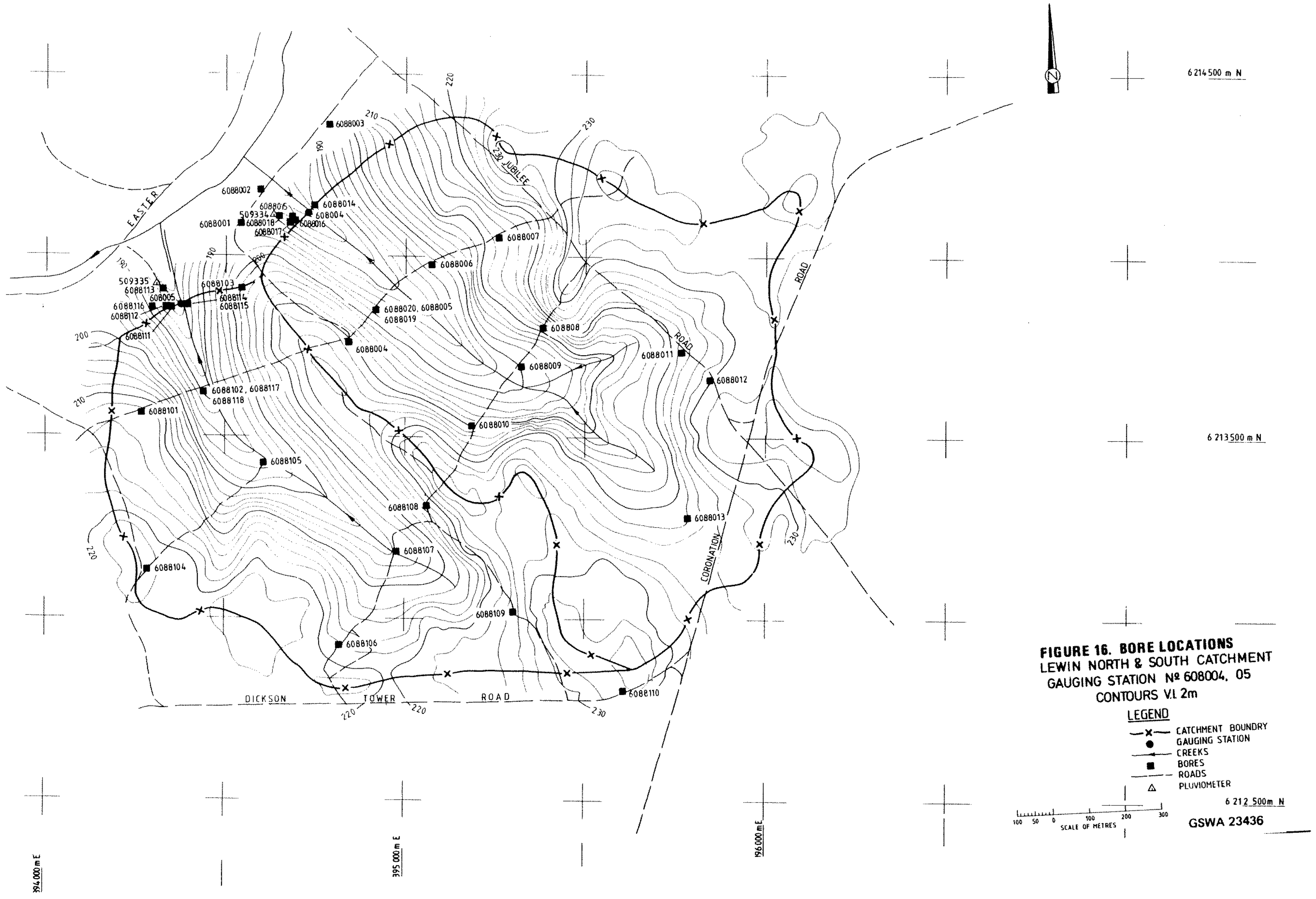


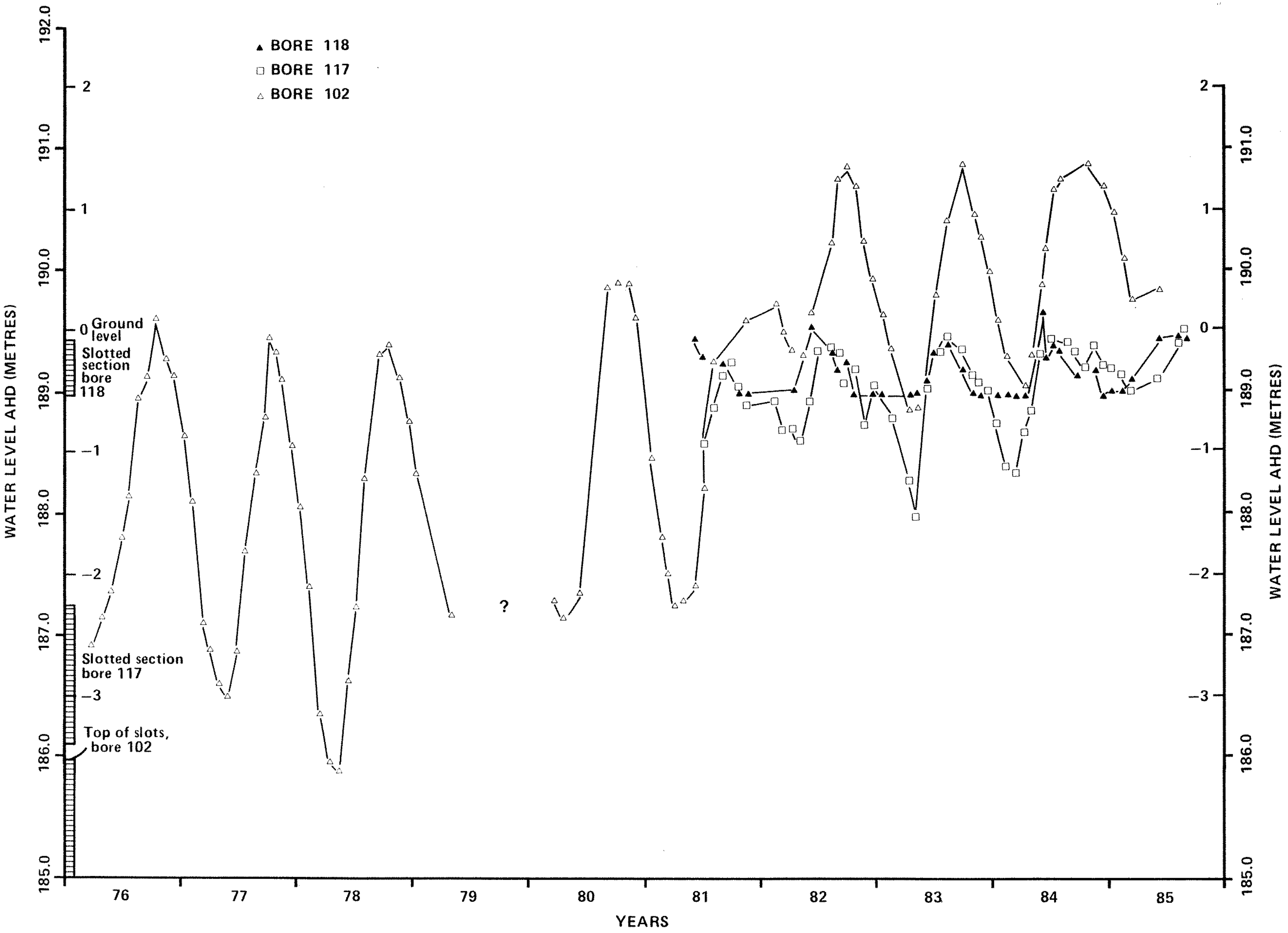
FIGURE 16. BORE LOCATIONS
LEWIN NORTH & SOUTH CATCHMENT
GAUGING STATION Nº 608004, 05
CONTOURS V.I. 2m

which occurred during 1980/81, before logging commenced (Fig. 18). The 1981 to 1985 average rise at Lewin South does not include the effect of the 1979 burn. At the Lewin North, March Road, and April Road North and South catchments there was a general decline in seasonal minimum water levels of less than 0.5 m from 1979 to 1981. The average rise at Lewin South probably underestimates the response to logging by about 0.5 m. An average rise of 2.8 m would be similar to the average response at the March Road and April Road North catchments.

The average decline from 1981 to 1985 at the control catchment (Lewin North) was 0.2 m, and is similar to the average decline at April Road South. This may indicate that the effect of the 1981 burn on the Lewin North catchment is limited to the early part of the post-logging period.

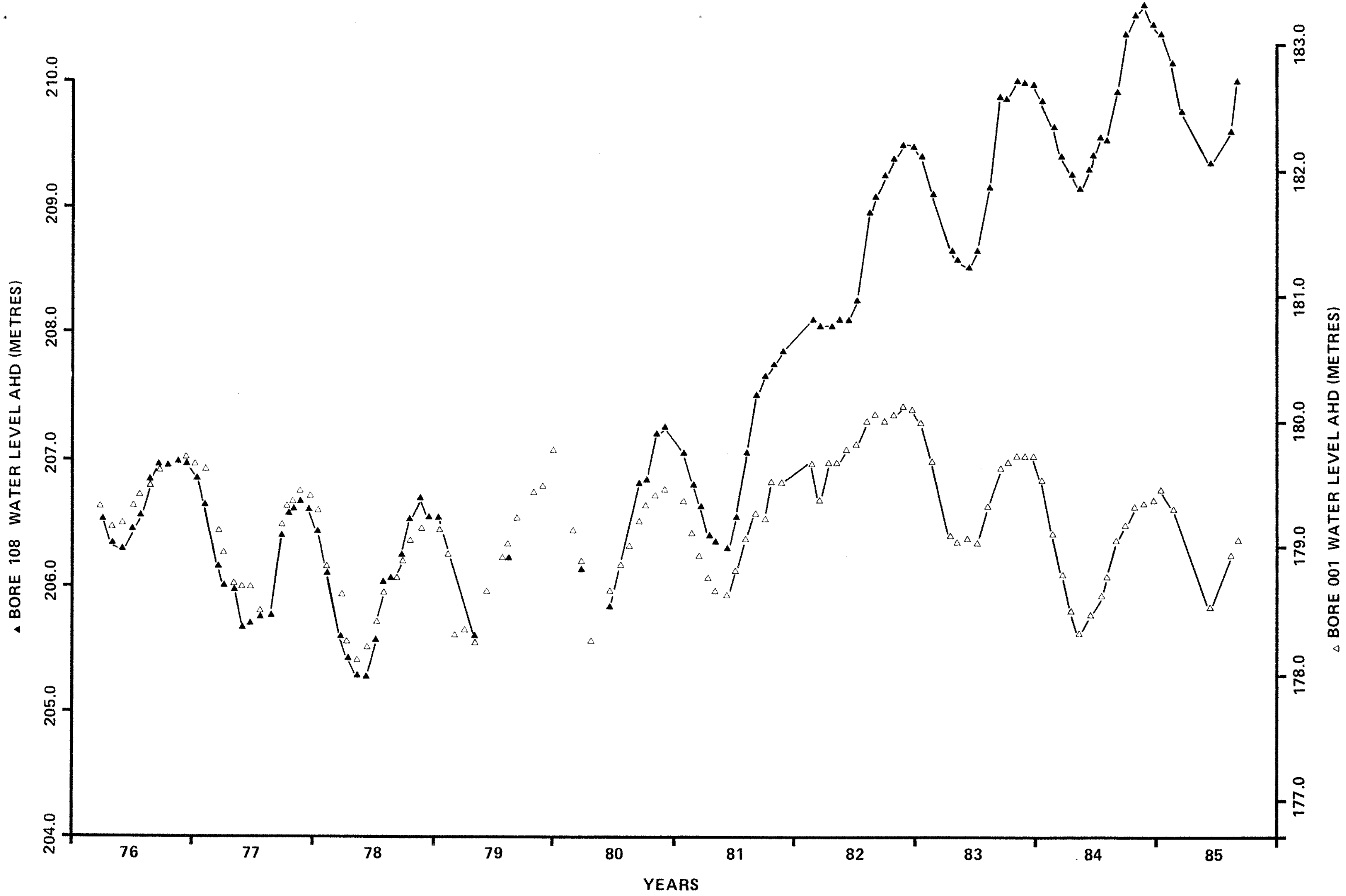
There is a general flattening of the rising trend of water levels in Lewin South several years after logging (Figs 17, 18). This may be due to regeneration of vegetation, or groundwater discharge by evaporation from the soil surface in areas where the water table has risen to near-surface.

A comparison of hydrographs (Fig. 17) for bores 102 (fully slotted), and 117, and 118 (water table) at the same site in the valley indicates upward flow and discharge of ground-water. There is a seasonal range in head difference of 0.9 to 1.6 m as the water table rises to the surface. Also, the seasonal rise in the fully slotted bore is slightly greater than that in the water table, and a similar response occurs during the declining phase of the hydrograph. These hydrographs reflect the complex relationships between changes in potential evaporation throughout the year, changes in actual evaporation with depth to water, and changes in storage and groundwater flow.



GSWA 23437

Figure 17 Groundwater hydrographs, bores 102 117 and 118



GSWA 23438

Figure 18 Groundwater hydrographs, bores 108 and 001

Net water-level change

There is a continuous increase in net water-level change from 1980 to 1984 at this catchment (Fig. 3). From 1984 to 1985 the net changes show all possible responses (increase, constant, reduction), however the general pattern appear to be a levelling out of the net water-level change. This is consistent with the flattening of the trend in minimum water level at the logged catchment and increasing water levels for the control, and may indicate increased transpiration by regenerating vegetation. Several more years monitoring are required before this can be determined.

The effect of the 1979 burn is to spread the treatment phase at this catchment over two years instead of one year as at other catchments. This does not influence the net water-level change. However, the 1981 burn has resulted in a disturbance to the control catchment, and the net water level change may be underestimated by 0.5 to 1 m.

Depth to water

The depth to water before logging at this catchment was about 10 m near the catchment divide, and decreases to less than 2 m in the valley (Fig. 41). The depth to water at the catchment outlet following logging is about 0.5 m, but rises to the surface during winter. Water levels are above ground surface along much of the valley after logging, which indicates an increasing head with depth. The water table in the valley is probably close to or at the surface for much of the year following logging.

Perched groundwater

The results from the shallow monitoring bore, 118, and the other bores at this site, indicate that bore 118 is monitoring the water-table response rather than perched groundwater (Fig. 17). Perching of groundwater may occur briefly at the beginning of winter at this site, however the sampling frequency is too short to detect this. No other shallow monitoring bores were established at this catchment.

Groundwater outflow

The rise in groundwater level at this catchment has been uniform, and has not resulted in significant increases in hydraulic gradient or changes in the water-level contour pattern. Using the increase in saturated thickness at the catchment outlet (Figs 40, 42; Appendix), the groundwater outflow is estimated to have increased by about 14%.

COMPARISON OF LOGGED CATCHMENTS

Groundwater-level response

The rise in seasonal minimum water levels has been smallest in the lower rainfall Yerraminnup South catchment, and greatest in the logged area of the April Road North catchment; significant rises have also occurred on the March Road and Lewin South catchments. The retention of vegetation in the valleys of the April Road North and Yerraminnup South catchments has limited the groundwater level rise beneath the vegetated area to about 53% of the rise in the logged area of Yerraminnup South, and 28% of the response in the logged area of April Road North.

There has been a general decline in groundwater levels on the control catchments during the post-logging period, however the 1985 seasonal minimum is generally higher than the 1984 minimum.

Net water-level change

There has been an increase in net water-level change on all catchments after logging, with the magnitude of the increases showing a similar pattern to the average water-level change. The net change for the Lewin South catchment probably underestimates the full logging response by 0.5 to 1 m because a fuel control burn was conducted in the control catchment in 1982. If this is taken into account, the data indicate that the greatest net water-level increase has occurred on the higher rainfall Lewin South catchment.

The trend in net water-level change is similar for all logged catchments, with a gradual increase until 1984, followed by general stabilization of levels to 1985. This may indicate that regeneration of vegetation is reducing recharge on the logged catchments, however further monitoring is required to determine if regeneration will reduce the net water-level increase in future years.

EFFECT OF CLIMATE ON GROUNDWATER LEVELS

The limited data, and similarity in rainfall at the Lewin and Sutton catchments, precludes the establishment of a relationship between rainfall and rise in water level or net water-level change following logging. However, the data indicate that the greatest increase in water level has occurred in the higher rainfall areas. The Project 2 studies have been conducted during a period when annual rainfall was below the long term average, and this sequence of lower rainfall is part of a longer (50-60 year) period of declining rainfall (Fig. 19). If logging were conducted during a period of higher rainfall, the rise in groundwater level may be greater, particularly in the drier Yerraminnup catchment.

Prior to logging, groundwater levels had been declining in response to the below average rainfall. During a sequence of higher rainfall years, groundwater levels would rise, and may influence the effect of logging on stream salinity.

For example, a sequence of above average rainfall years on the Yerraminnup South catchment may result in a rise in groundwater level. If logging were conducted during this time, a further rise in groundwater level may occur, and groundwater may discharge to the stream. If rainfall continued to be high during the post-logging period, the additional run-off may dilute the groundwater component of streamflow and limit the increase in stream salinity. A reduction in rainfall during the post-logging period may result in a significant increase in stream salinity in the drier northeastern sector. This effect would continue until increased evapotranspiration from the regenerating vegetation lowered groundwater levels to below the stream bed.

EFFECT OF LOGGING ON GROUNDWATER SALINITY

Comparison of salinity changes at individual bores cannot be made because of bore construction and sampling method. Leakage of fresh water down the annular space between hole and casing has been discussed earlier, whilst the sampling method involved bailing a sample from the bottom of the bores for salinity determination.

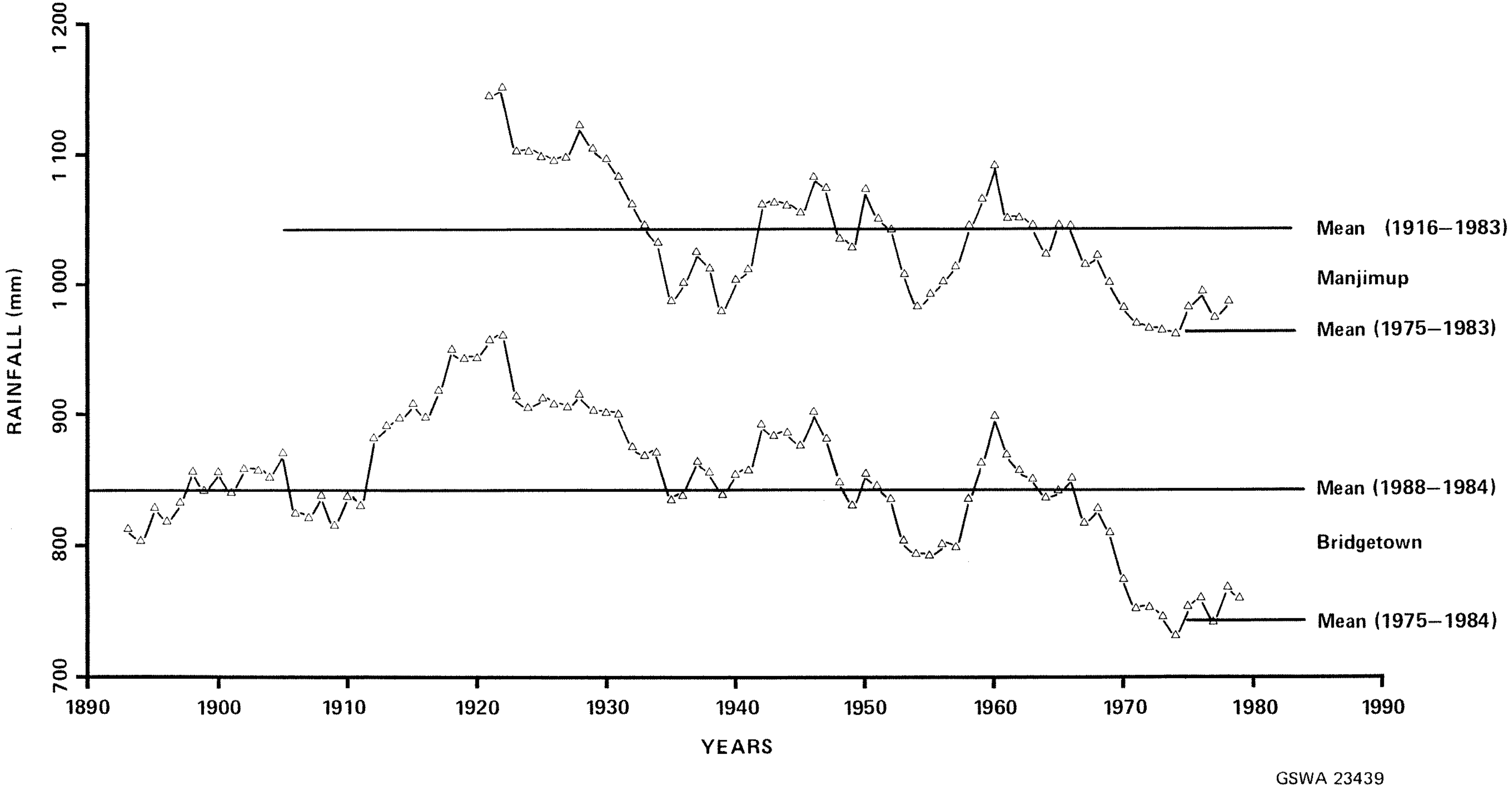


Figure 19 Manjimup and Bridgetown 11-year moving average of annual rainfall

Changes in groundwater salinity after logging are likely to occur in the zone over which the water table rises rather than at the base of the saturated interval. Samples from the bottom of a bore are therefore unlikely to reflect changes which result from logging activities. This is illustrated by the results from bores 205 and 218 at the March Road catchment (Fig. 20). The groundwater salinity in the fully slotted bore (205) was 1200 mgL^{-1} total soluble salts (TSS), and did not change following logging. When the water table rose into the slotted section of bore 218, the groundwater salinity was 12 800 mgL^{-1}. This is similar to the soil salinity over this interval, and reflects remobilization of stored soil salt by the rising water table. Although bore 205 is slotted over the zone of high salt storage, the hydraulic head in this bore after logging is higher than the water table (Figs 14, 20). Because of the hydraulic head difference, water will flow from the casing to the formation, and a sample collected just below the water level in this bore would not reflect the groundwater salinity in the adjacent formation.

Similar conditions exist for bores 102 and 117 on the Lewin South catchment, and construction details are shown on Figure 17. Soil salinity was not measured over the upper 4 m of the profile at this site, but at 4.3 m the soil salinity was 1844 mgL^{-1}, and decreased to 570 mg L^{-1} at 5 m. Below this depth, soil salinity was in the range 100-400 mgL^{-1}. The groundwater salinity in the fully slotted bore (102) was about 100 mgL^{-1}, and there was little change following logging. The groundwater salinity in the water-table bore (117) was about 2300 mgL^{-1} after logging, which reflects the higher salt storage in the upper part of the profile. Following logging, the water table reaches the surface during winter at this site, and the range of groundwater salinity of the shallow (0.76 m deep) monitoring bore (118) is 100 to 370 mgL^{-1}. This

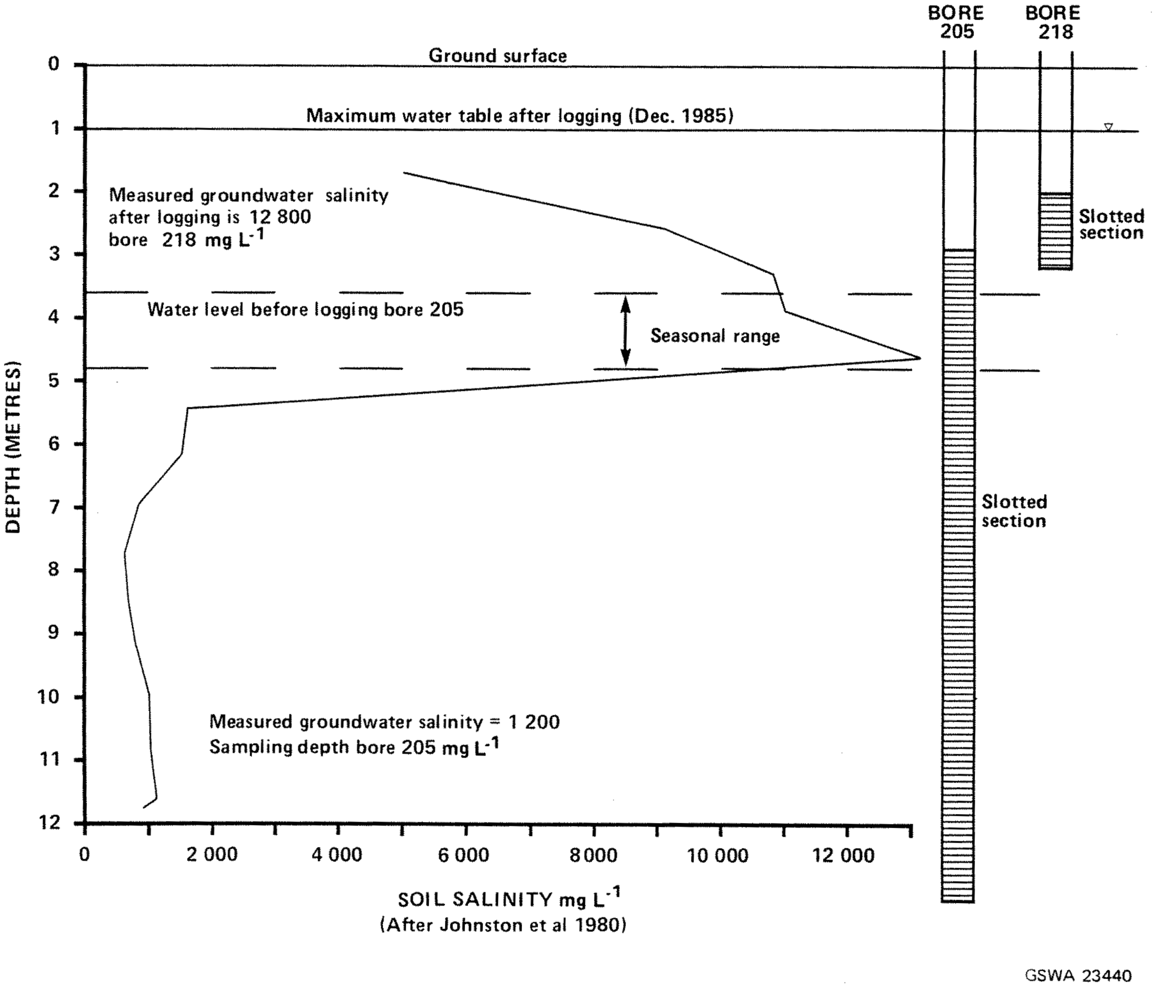


Figure 20 Soil salinity and groundwater salinity, bores 205 and 218, March Road catchment

TABLE 6. SOIL AND GROUNDWATER SALINITY OF LOGGED CATCHMENTS

	Maximum Soil Salinity		Groundwater Salinity		
			Pre-logging(1)	Post-logging	
Bore	Depth (m)	TSS (mgL^{-1})	TSS (mgL^{-1})	Depth to Water (m)	TSS(2) (mgL-^{1})
YERRAMINNUP CREEK SOUTH					
101	5.2	13 600	7 400	3.4	13 000
103	7.5	10 500	-	30	8 000
111	5.5	2 000	550	12.5	550
115	5.4	20 000	1 300	4.7	20 000
116	8.4	14 383	5 500	12.5	-
117	4.7	9 300	2 400	11.8	2 500
APRIL ROAD NORTH					
301	1.8	3 446	230	1.8	2 290
302	8.5	11 786	55?	9.7	5 500
303	5.0	8 130	90-400	4.4	5 380
304	4.4	9 787	550	6.2	550
305	2.5	8 789	1 700	0.4	6 205
307	4.3	9 121	210	6.8	2 460
308	7.6	7 593	300	11.1	1 000
309	5.4	5 400	800	8	2 300
MARCH ROAD					
201	4.7	9 310	370	7.7	1 000
202	3.4	12 400	370	2.9	10 000
205	4.6	13 169	1 200	1.8	12 800(3)
206	3.3	8 165	550	0.7	8 000
207	5.0	7 619	80?	9.3	1 500
LEWIN SOUTH					
101	11.1	14 454	925	12.9	11 000
102	4.3	1 844	100	0.2	2 300(3)
104	6.6	955	55	6.4	820
105	4.4	973	350	0	800
106	3.4	6 527	650	4.7	1 800
108	7.7	7 097	240	9.1	1 430

(1) Typical of values measured in bore casing
(2) Estimated from soil salinity over zone of water-table rise
(3) Measured in shallow bore
? Low value with respect to soil salinity of profile, may indicate leakage of fresh water from surface
* Unusually high value for this catchment

indicates dilution of salt or the groundwater by rainfall recharge.

TABLE 7. TYPICAL STREAM SALINITIES AFTER LOGGING (1982-1985)

Catchment	Maximum	Flow weighted average
	Range (mgL^{-1}, TSS)	
Yerraminnup Creek South	135- 365	81-207
April Road North	230- 370	111-140
March Road	1240-2300	181-314
Lewin South	190- 275	103-182

An assessment of the possible increase in groundwater salinity has been made from the soil salinity of the interval over which the water table rose, and comparing this with the measured groundwater salinity before logging (Table 6). The results from bore 118 on the Lewin South catchment indicate that the salinity of groundwater in near-surface zones may be reduced by rainfall infiltration. This is also reflected by the maximum stream salinities following logging (Table 7), which are less than the post-logging groundwater salinities by at least an order of magnitude.

The absence of groundwater discharge to the stream in the Yerraminnup Creek South catchment is reflected by the low stream salinity and similarity between maximum and average stream salinity. Although the processes of salt leaching and discharge are not well understood, the difference between maximum stream salinity and groundwater salinity for the remaining catchments indicate that either groundwater discharge is diluted in streamflow, or is at a lower salinity than indicated by soil-salt storage. The lower flow-weighted average salinities reflect the small volume of the higher salinity flows.

The highest post-logging groundwater salinities, as inferred from the soil salt storage over the zone of water table rise, occur at the Yerraminnup South catchment. However, the groundwater does not discharge to the stream. The greatest increase in groundwater salinity has occurred in the Sutton catchments (April Road North, March Road) where the water table has risen into zones of higher salt storage. The greatest impact on stream salinity (Table 7) occurred on the March Road catchment where groundwater salinity has increased in areas where the water table is near the surface. Although groundwater salinities have increased, and the water table has risen to near surface in the valley of the Lewin South catchment, the impact on stream salinity has been ameliorated by the generally lower groundwater salinity and increases in stream-flow generated by run-off and perched flow (Table 7).

Regeneration of vegetation following logging has potential to increase stream salinity for a short period (several years) until additional evapotranspiration results in a lowering of groundwater levels. The observed rise in groundwater levels is a cumulative response over four years. During regeneration, leaf area will increase, and may result in a decrease in the run-off and perched groundwater component of streamflow due to higher interception losses. If groundwater base-flow remains essentially constant, stream salinity may increase because of a reduction in the lower salinity component of the stream flow. There is insufficient data to determine the significance of this effect, but it is likely to be small and of a temporary nature as regenerating vegetation may take several years to lower groundwater levels.

The salinity of perched groundwater is similar in all catchments, and is generally 55-110 mgL^{-1} or four to ten times rainfall salinity. Mixing of rainfall recharge and salt discharged from groundwater in the Lewin South catchment results in perched groundwater salinities of 100-370 mgL^{-1}. Because of the limited data it is not possible to draw conclusions about the effect of logging on the perched groundwater system.

CONCLUSIONS

1. Logging of the Project 2 catchments has resulted in a rise in groundwater levels. Seasonal minimum groundwater levels in the control catchments have declined slightly during the post-logging period.

2. Retention of a vegetated area in the valleys of the Yerraminnup South and April Road North catchments has limited or delayed the rise in groundwater levels beneath those areas.

3. The increase in net water-level change was smallest on the low rainfall Yerraminnup South catchment, and, if the effect of a fuel reduction burn on the Lewin North catchment is included, the increase was greatest on the high rainfall Lewin South catchment.

4. Two to three years after logging, there appears to be no further increase in net water-level change on all catchments, and there is a general flattening of the rising trend of groundwater levels. This indicates that the regenerating vegetation on the logged catchments is reducing recharge, but at present has not produced a decline in groundwater levels.

5. Perched groundwater was observed in all logged catchments, and its occurrence coincides with periods of higher winter rainfall. It is not possible to determine the effect of logging on this system because of the limited monitoring.

6. Logging can result in an increase in groundwater salinity near the water table as rising water levels remobilize salt that is stored in the unsaturated zone. The greatest increase was observed in the Sutton block catchments where soil salinity in the zone of water-table rise was much higher than the pre-logging groundwater salinities. The highest measured groundwater salinities occur in the Yerraminnup South catchment, and are lowest on the Lewin South catchment.

7. The greatest impact of logging on stream salinity has taken place in the March Road catchment where groundwater discharges to the stream and significant increases in groundwater salinity have occurred. Groundwater discharges to the streams in the April Road North and Lewin South catchments, but the salinity of the discharge is reduced by rainfall, and maximum stream salinities after logging are less than 400 mgL^{-1}. Groundwater did not discharge to the stream after logging on the Yerraminnup Creek South catchment.

8. Maximum stream salinities after logging are much lower than the estimated groundwater salinity at the water table. This indicates that the groundwater discharge is diluted by rainfall infiltration to the perched aquifer.

9. The logging activities for the Project 2 study have been conducted during a period of low annual rainfall. The prevailing climatic conditions and depth to groundwater at the time of logging will influence the impact of logging on stream salinities.

RECOMMENDATIONS

1. The present level of monitoring should be continued on all Project 2 catchments for at least five years. The data should be reviewed in 1990/91 to determine the full effect of logging and regeneration on water quality.

2. The Yerraminnup and Sutton block control catchments should be left uncut and monitored for an extended period. This will provide a base-line data set for groundwater levels and salinities in this salt-sensitive area under a range of climatic conditions.

3. The retention of stream reserves or vegetated buffer strips appears to have limited the rise in water level following logging, and is a technique which could be applicable to logging operations in salt-sensitive areas.

4. Monitoring of bores 218 (March Road), and 117 and 118 (Lewin South) should be continued until the bores become dry. Pumped samples should be collected twice yearly to determine if leaching of salt is occurring.

5. Future research on groundwater in the weathered granitic terrain of the Yilgarn Block should fully utilize the experience in groundwater monitoring gained from these studies. Monitoring networks should include at least two monitoring points at each location to provide information on head variation with depth. The additional piezometers which were installed above the pre-logging water table have provided valuable information. This design should be incorporated in future studies where a rise in water level is anticipated.

6. The design of a monitoring network should be an evolving process that involves review and addition of monitoring points at sites, or additional sites established, to ensure that the monitoring is adequate to meet the research objectives.

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APPENDIX A

NOTES AND TECHNICAL DIAGRAMS FOR

PROJECT 2 CATCHMENTS

BORE NOMENCLATURE

Bores are identified by the Australian Water Resources Council (AWRC) numbering system. The original system was based on seven numerics, and is used on the accompanying plans. The first three digits refer to the river basin, the fourth digit is station type, with groundwater indicated by 8 or 9, and the last three digits are sequentially numbered bores.

This system has now been modified with an 8 digit station number referring to groundwater stations. The river basin identification in the first three digits has been retained, and an additional numeric is added before station type (which is now obsolete). For example, station number 6078001 becomes 60718001.

The borefield numbers, in the eight digit system, with the additional numeric bracketed, are:

Yerraminnup Creek: 607	
North catchment	607(1)8001 - 607(1)8023
South catchment	607(1)8101 - 607(1)8130
Sutton: 607	
April Road North	607(1)8301 - 607(1)8318
April Road South	607(1)8401 - 607(1)8417
March Road	607(1)8201 - 607(1)8219
Lewin: 608	
North	608(1)8001 - 608(1)8020
South	608(1)8101 - 608(1)8118

BASEMENT TOPOGRAPHY

The top of basement contours are based on the limit of auger penetration when the bores were established and do not include moderately weathered rock. Where bedrock was not reached or drilling may have stopped on fresh boulders in the weathered profile, basement contours have been modified using a subjective assessment of the contours in the catchment.

WATER LEVEL CONTOURS

Water levels are measured in bores which are slotted over the full saturated thickness. The water levels are not necessarily a true indication of the water table position, particularly in valley sites where water levels may be above ground level.

The water-level contours generally conform to surface topography and are influenced by variations in saturated thickness, and distribution of recharge and discharge areas. The primary controls used to determine the pattern of water-level contours over a catchment area were: water level elevation, surface topography, and saturated thickness.

Drawing of the water-level contours is based on the assumption that over an area of several hundred hectares, the spatial distribution of measured water levels will reflect some average hydraulic conductivity for the saturated weathered material. The validity of this assumption decreases with shorter distance between bores because of local variations in hydraulic conductivity.

SATURATED THICKNESS

The saturated-thickness maps are produced by overlaying basement topography and water-level contour plans, and calculating the saturated thickness at the intersection of the contours. Although the method generates additional data points, it also incorporates any contouring discrepancies in basement or water level.

The zero saturated-thickness contour defines the boundary between groundwater in the weathered material and groundwater in fractures and joints of moderately weathered to fresh basement. The movement of water in the basement is poorly understood, and for the purpose of this report is considered to be negligible in comparison to groundwater movement in the weathered material.

DEPTH TO WATER

The contours of depth to water are generated from surface topography and water-level contour maps in a similar way to the saturated-thickness contours. Because of the inherent errors in the water-level contours, the depth-to-water contours are a guide to identifying areas where groundwater may discharge at the surface.

WATER LEVEL CHANGE

The change in groundwater level following logging is included on the water-level contour and depth-to-water maps for individual sites on each catchment rather than water-level change maps. Although water-level change maps can be generated by overlaying successive water-level contour maps, the lack of control for the water-level maps and possible contouring discrepancies may result in an erroneous depiction of water-level change. The change in groundwater level is the change from the 1981 groundwater level rather than the change in seasonal minimum value.

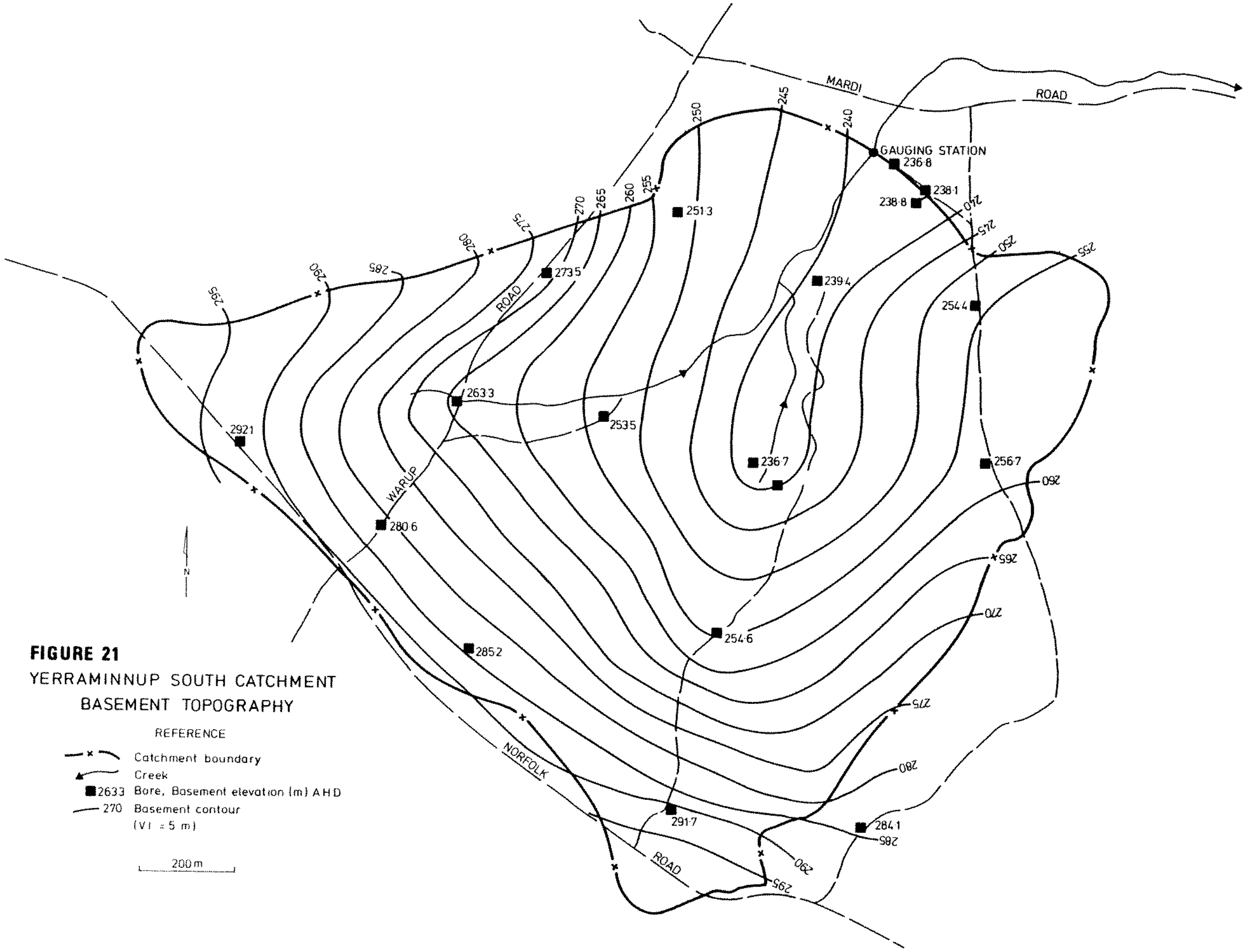


FIGURE 21

YERRAMINNUP SOUTH CATCHMENT
BASEMENT TOPOGRAPHY

GSWA 23441

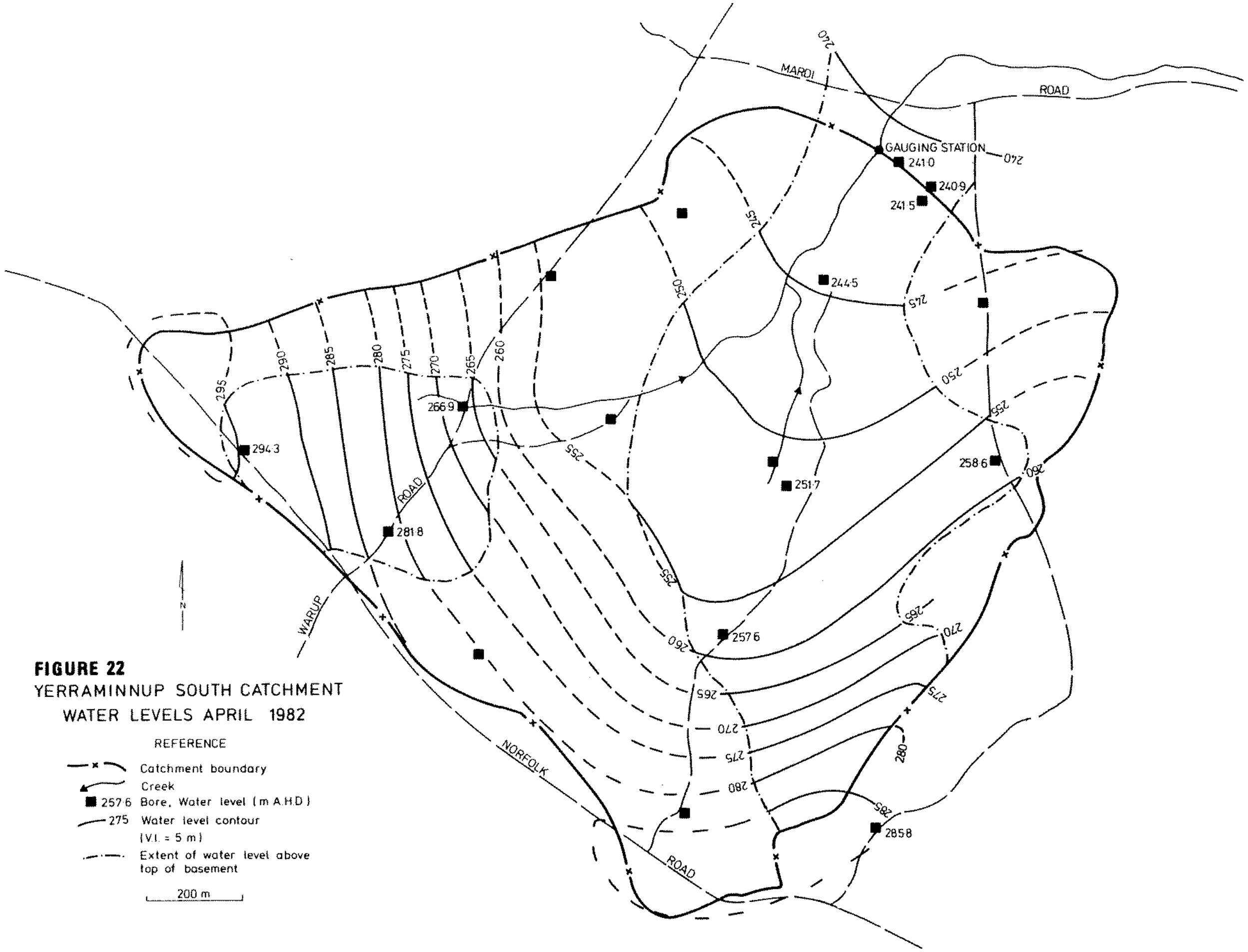


FIGURE 22
YERRAMINNUP SOUTH CATCHMENT
WATER LEVELS APRIL 1982

GSWA 23442

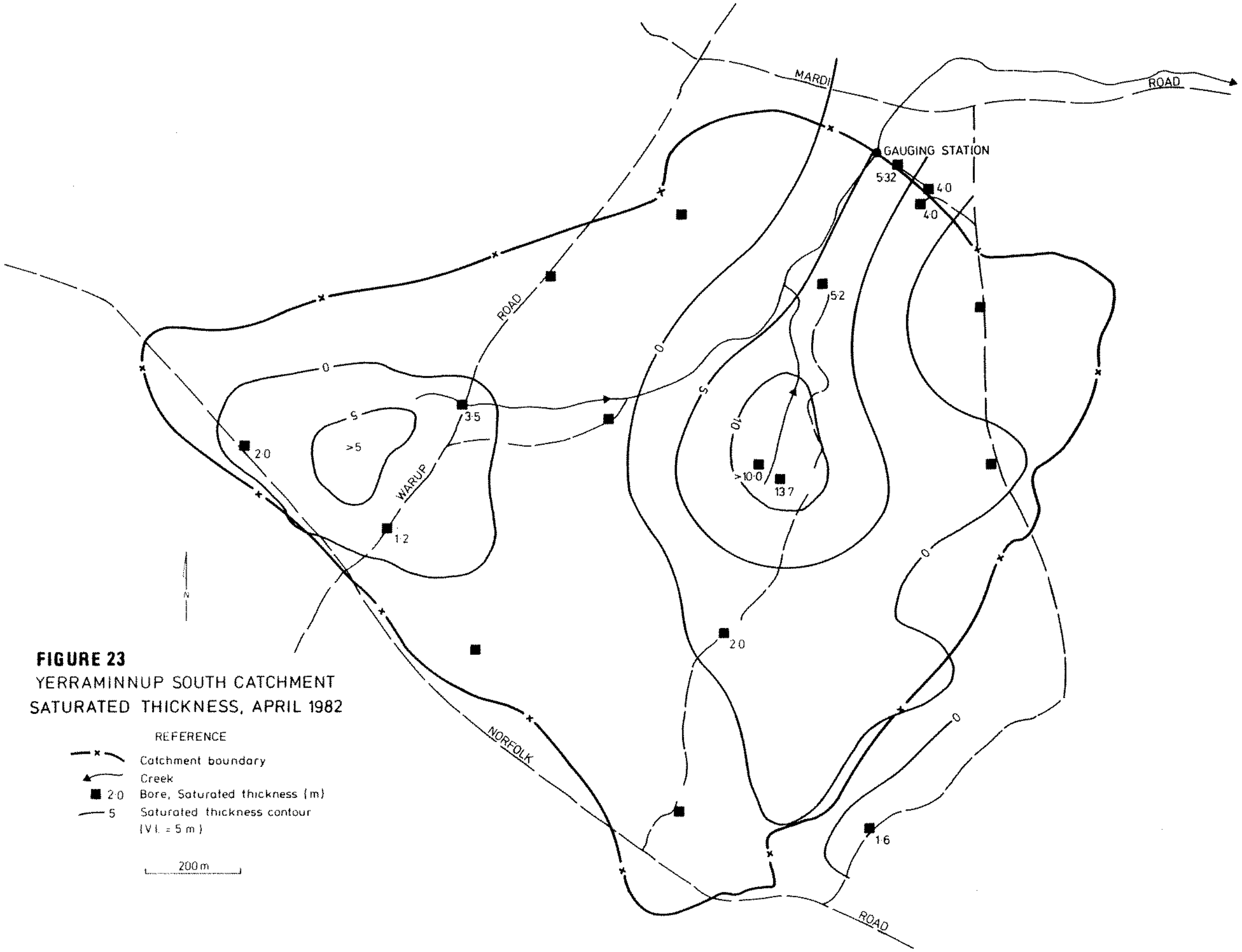


FIGURE 23
YERRAMINNUP SOUTH CATCHMENT
SATURATED THICKNESS, APRIL 1982

GSWA 23443

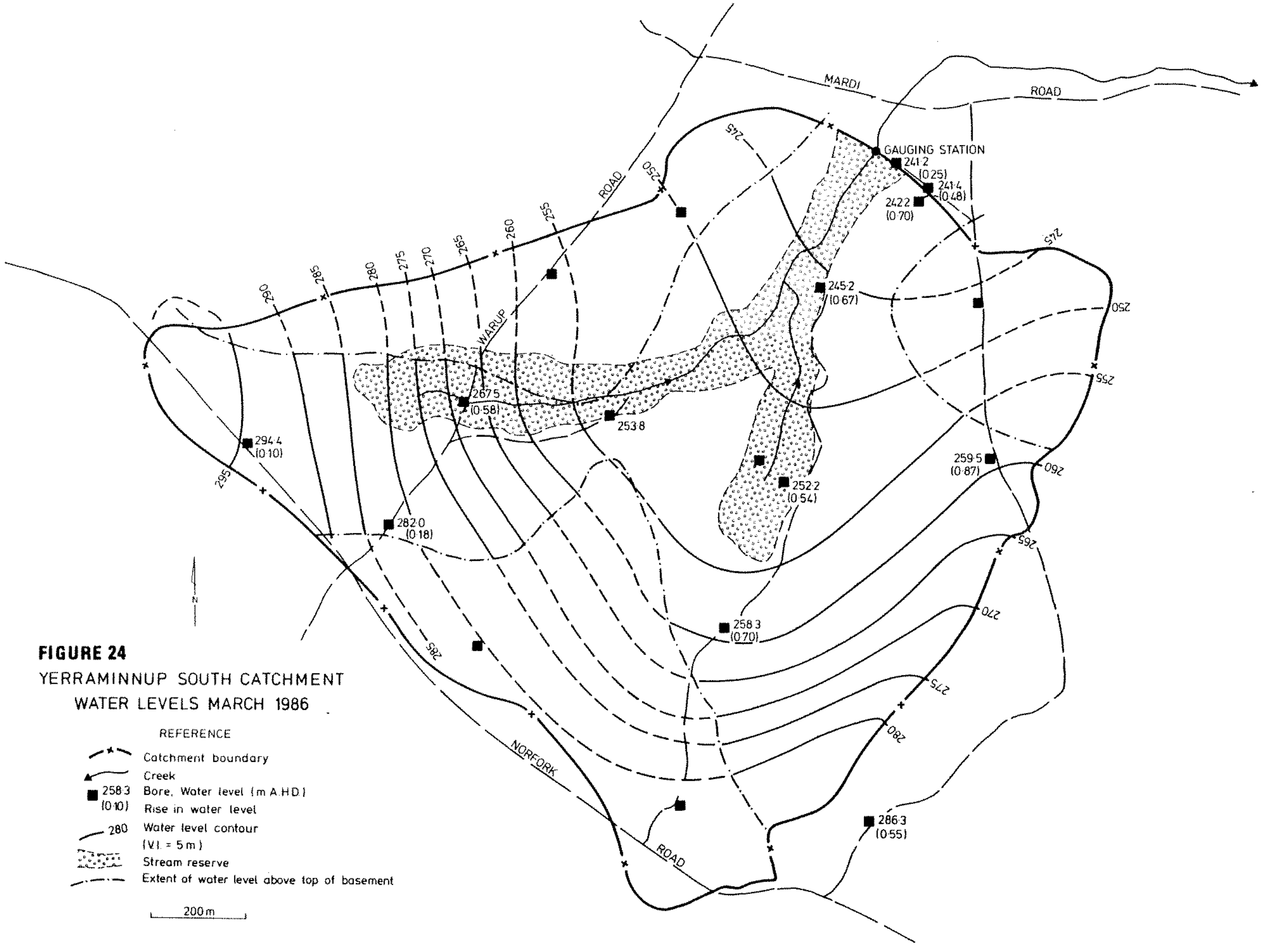


FIGURE 24
YERRAMINNUP SOUTH CATCHMENT
WATER LEVELS MARCH 1986

GSWA 23444

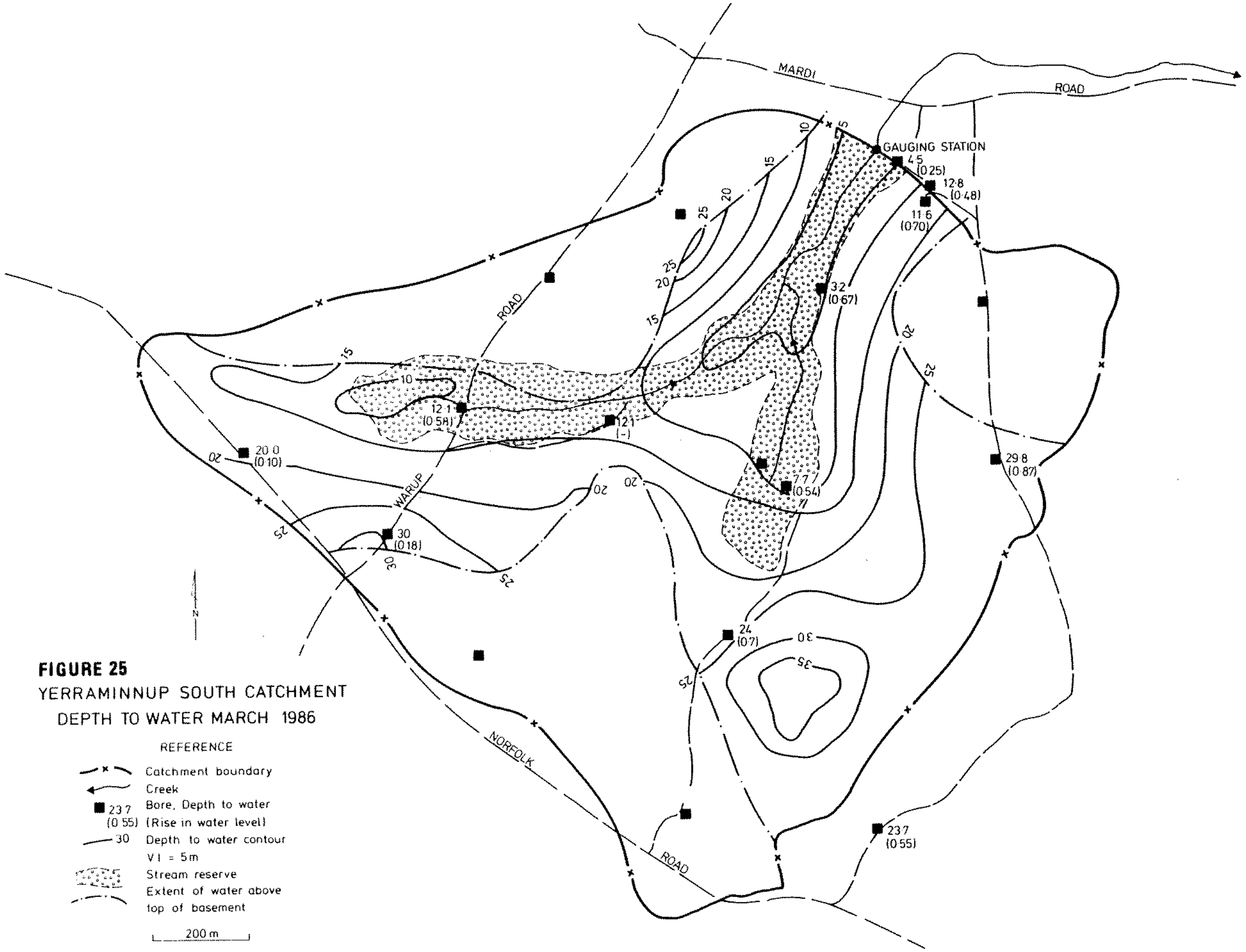


FIGURE 25

YERRAMINNUP SOUTH CATCHMENT
DEPTH TO WATER MARCH 1986

GSWA 23445

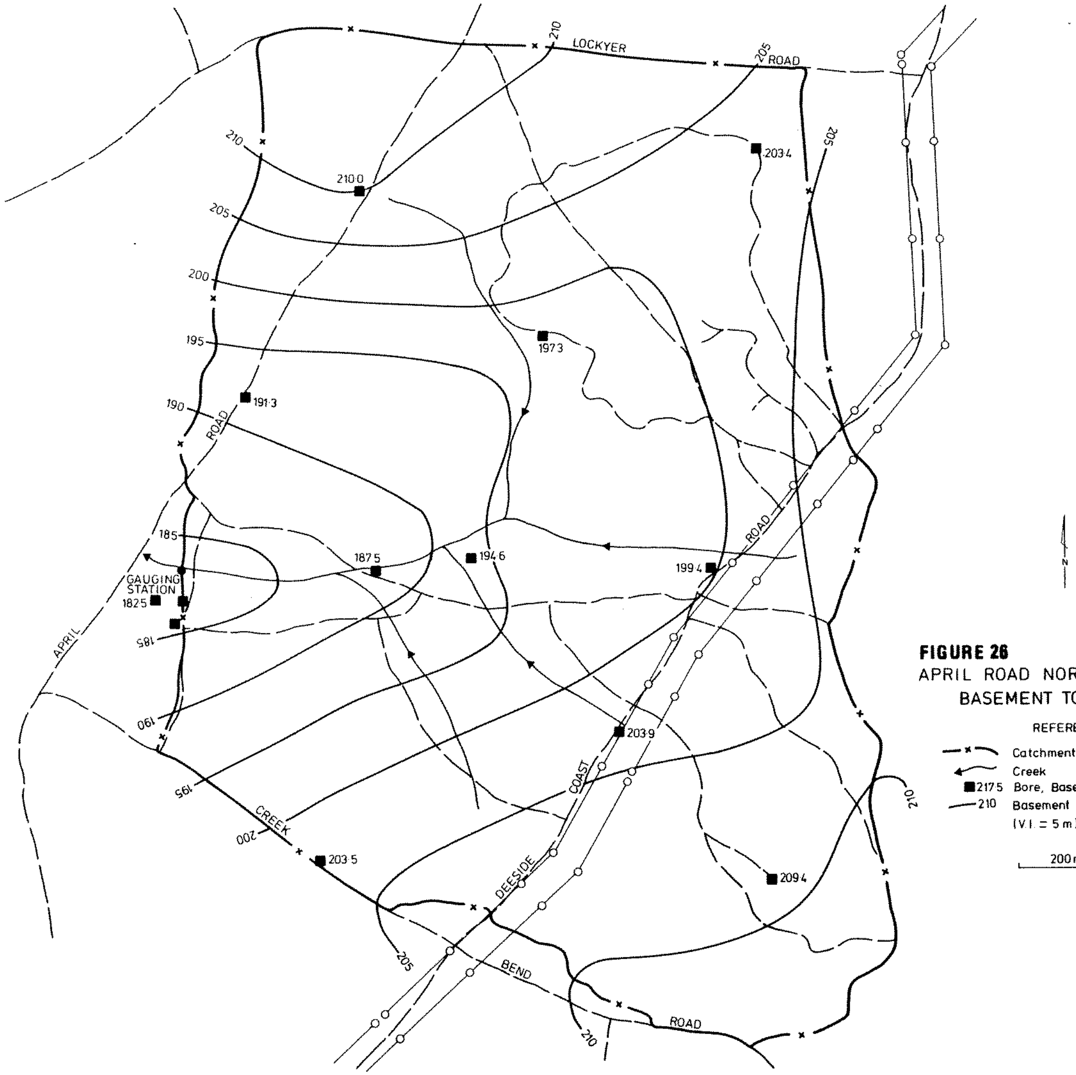


FIGURE 26
APRIL ROAD NORTH CATCHMENT
BASEMENT TOPOGRAPHY

REFERENCE

—×— Catchment boundary
← Creek
■217·5 Bore, Basement elevation (m A.H.D.)
—210 Basement contour
(V.I. = 5 m)

200 m

GSWA 23446

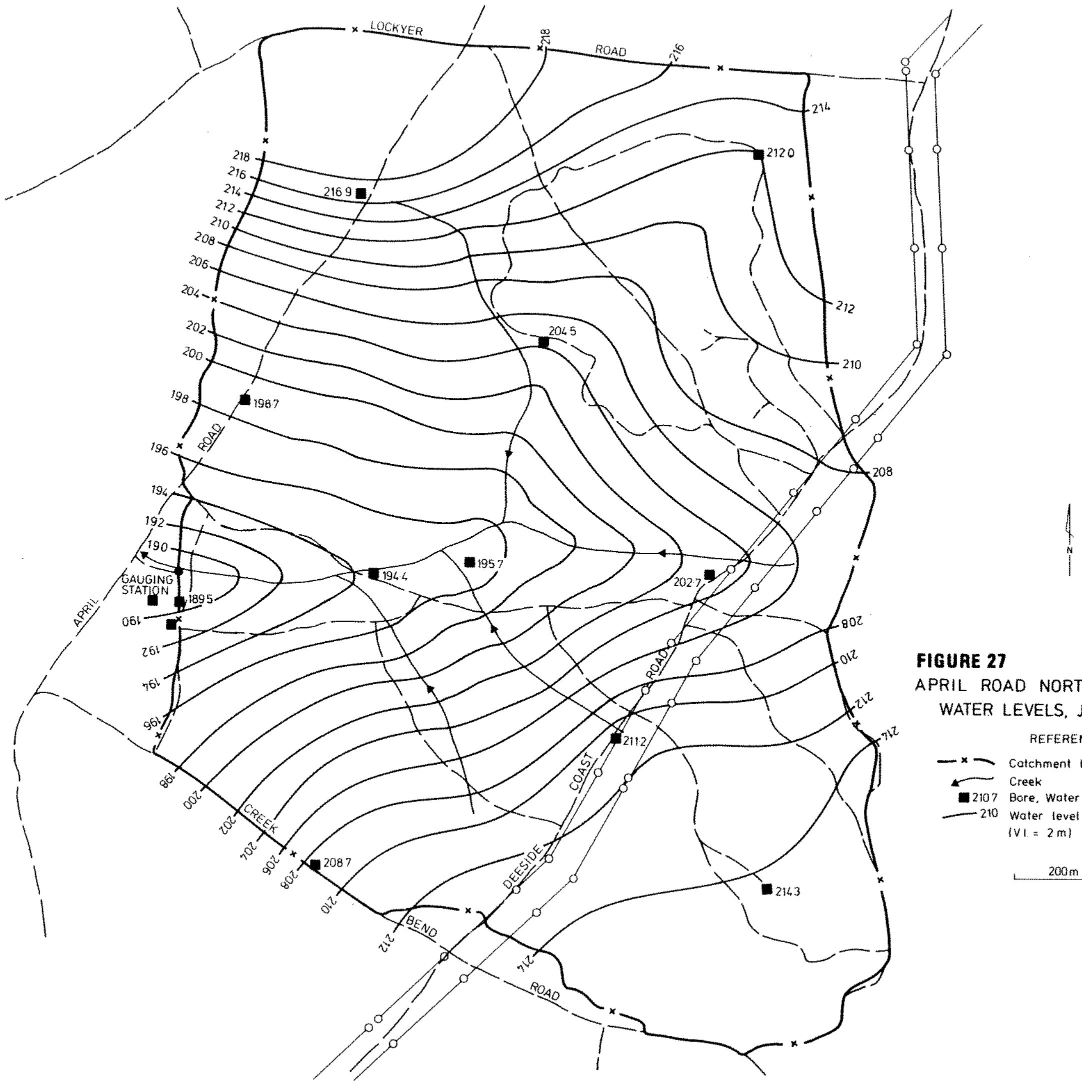


FIGURE 27
APRIL ROAD NORTH CATCHMENT
WATER LEVELS, JUNE 1981

REFERENCE
Catchment boundary
Creek
■ 210.7 Bore, Water level contour (m A.H.D.)
210 Water level contour
(V.I. = 2 m)
200 m

GSWA 23447

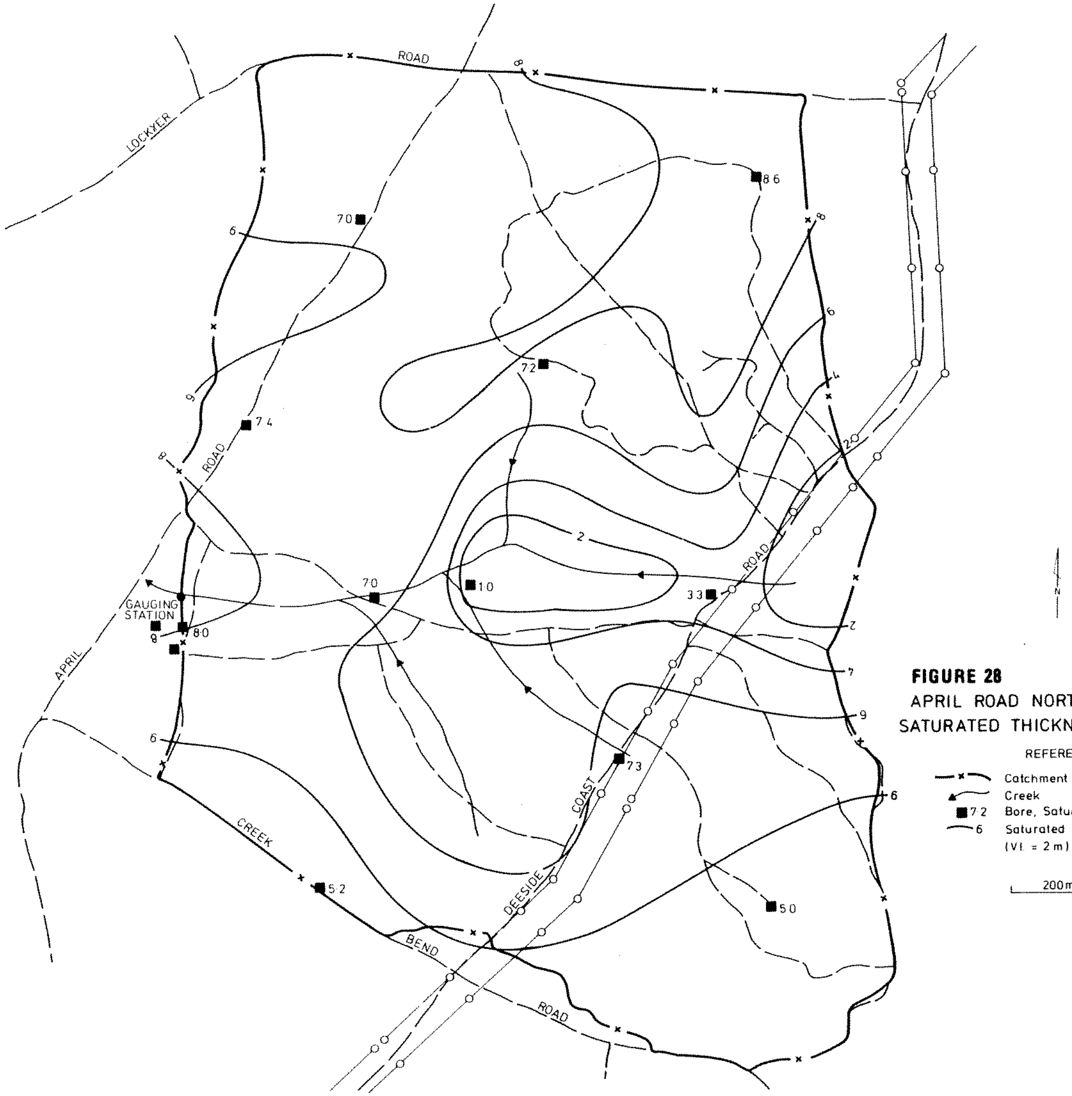


FIGURE 28
APRIL ROAD NORTH CATCHMENT
SATURATED THICKNESS, JUNE 1981

GSWA 23448

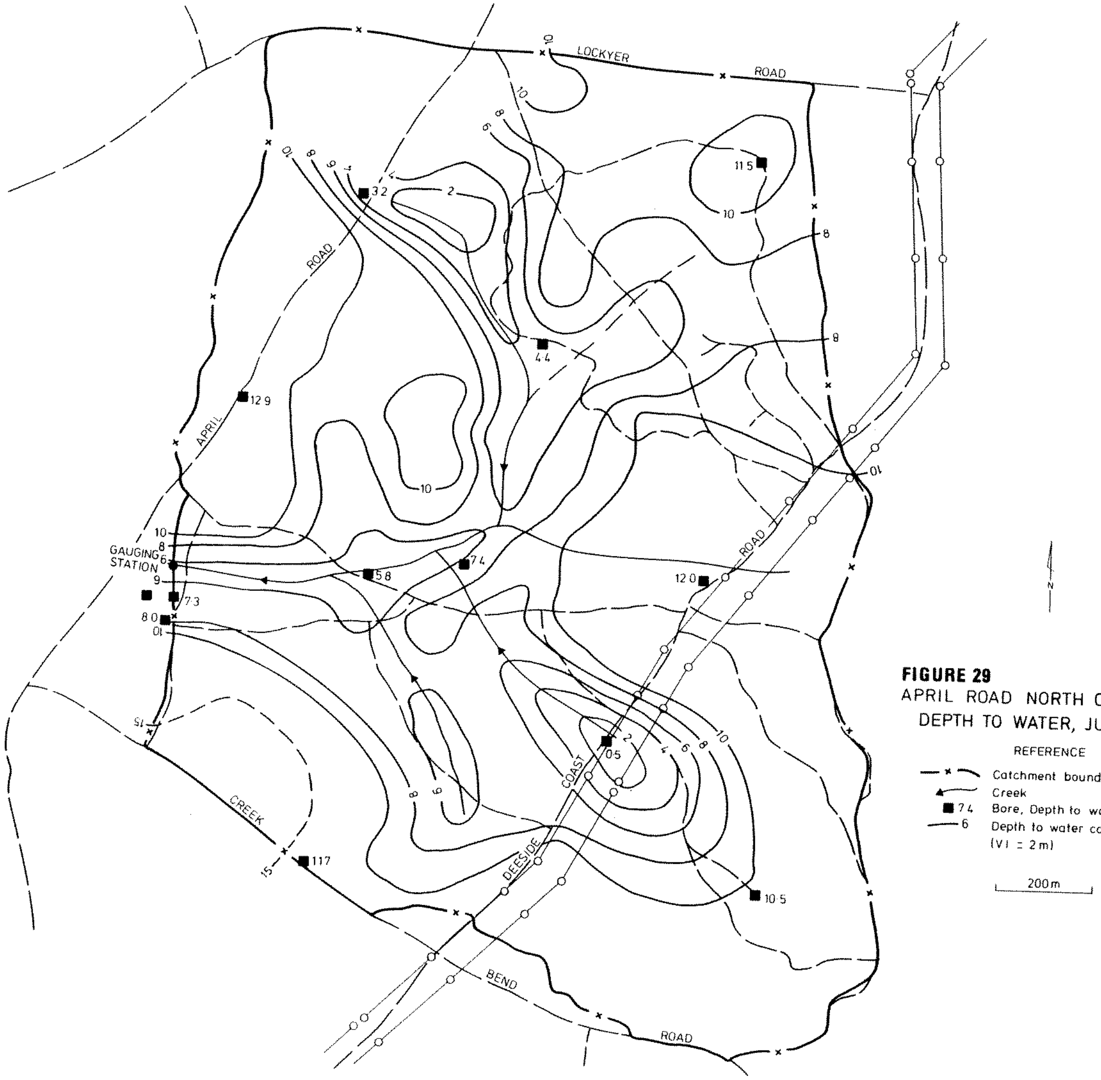


FIGURE 29
APRIL ROAD NORTH CATCHMENT
DEPTH TO WATER, JUNE 1981

GSWA 23449

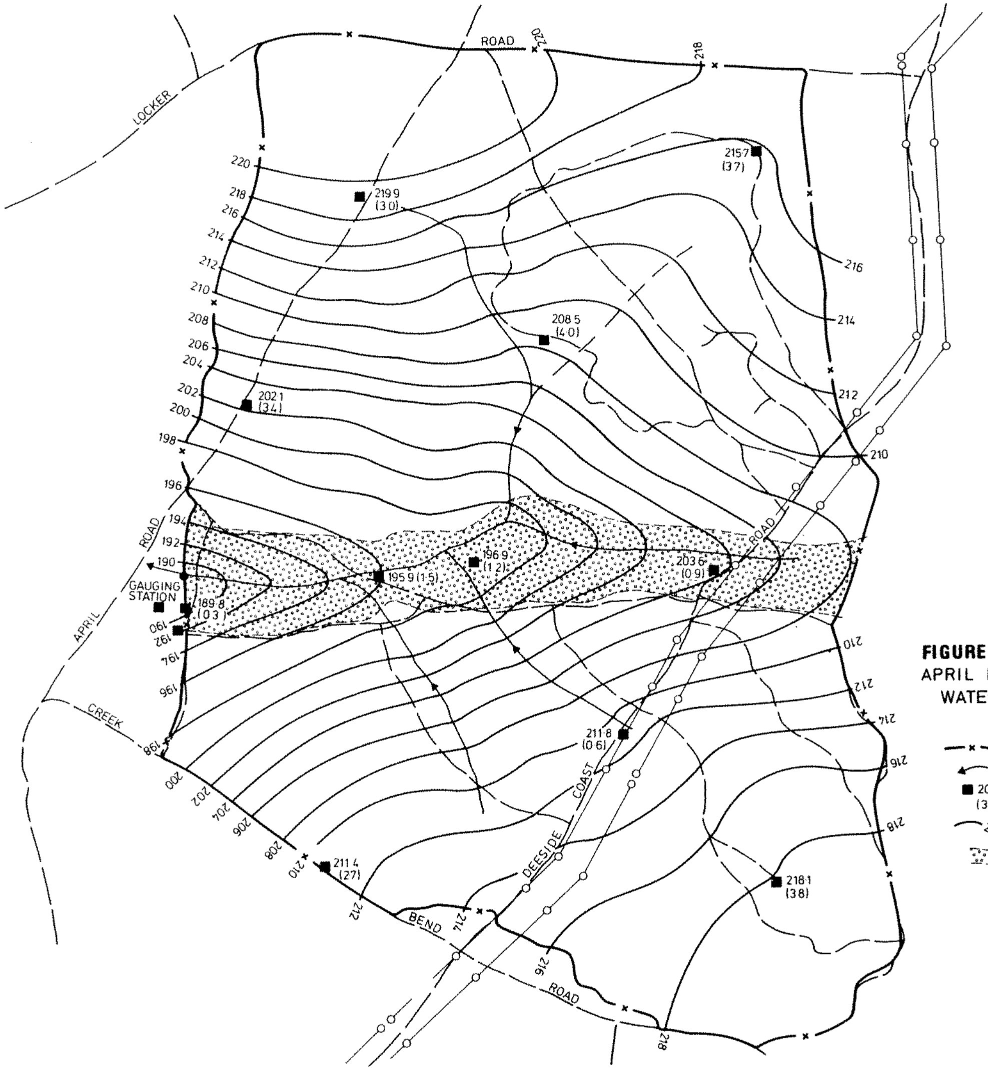


FIGURE 30
APRIL ROAD NORTH CATCHMENT
WATER LEVELS, JUNE 1985

REFERENCE

GSWA 23450

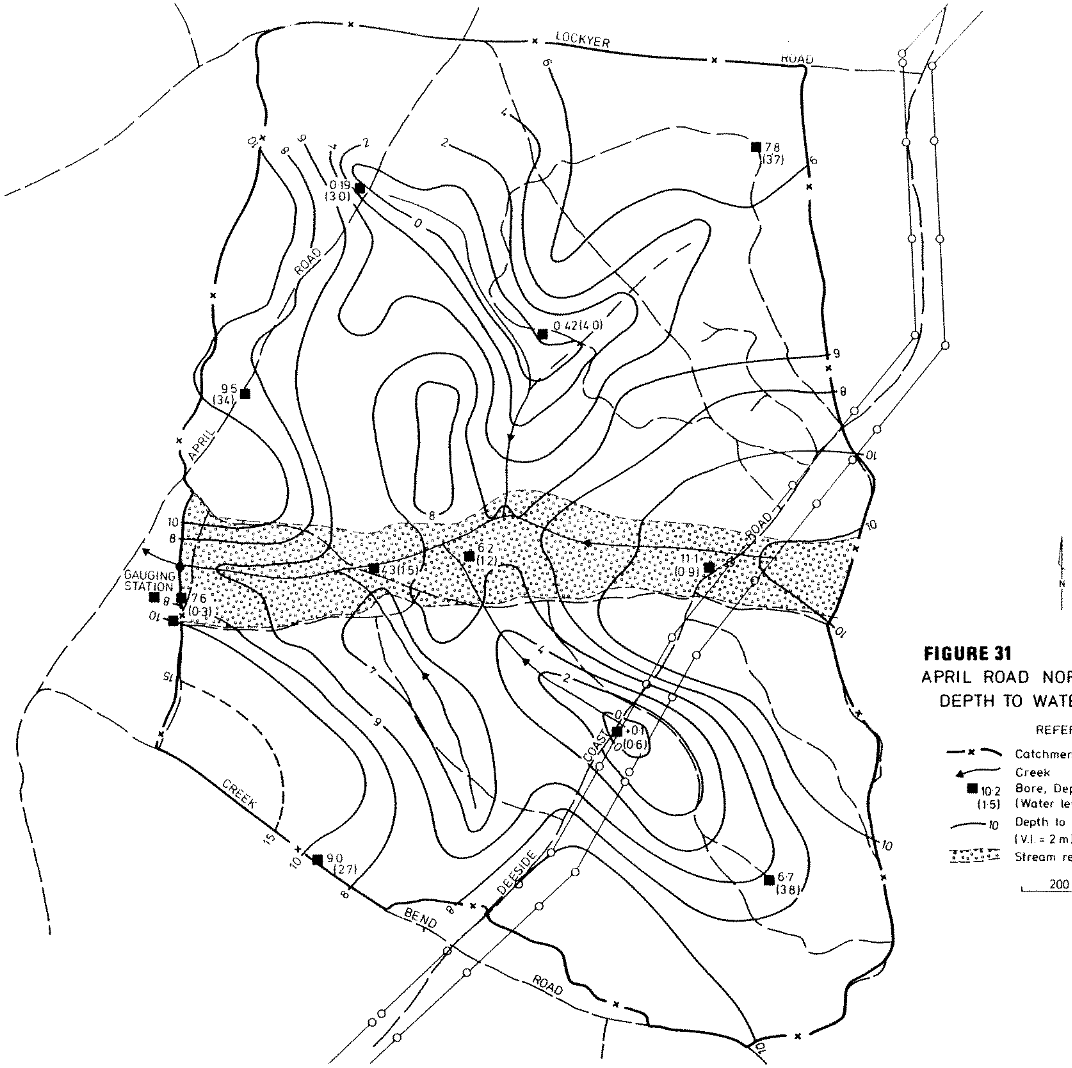


FIGURE 31
APRIL ROAD NORTH CATCHMENT
DEPTH TO WATER, JUNE 1985

REFERENCE

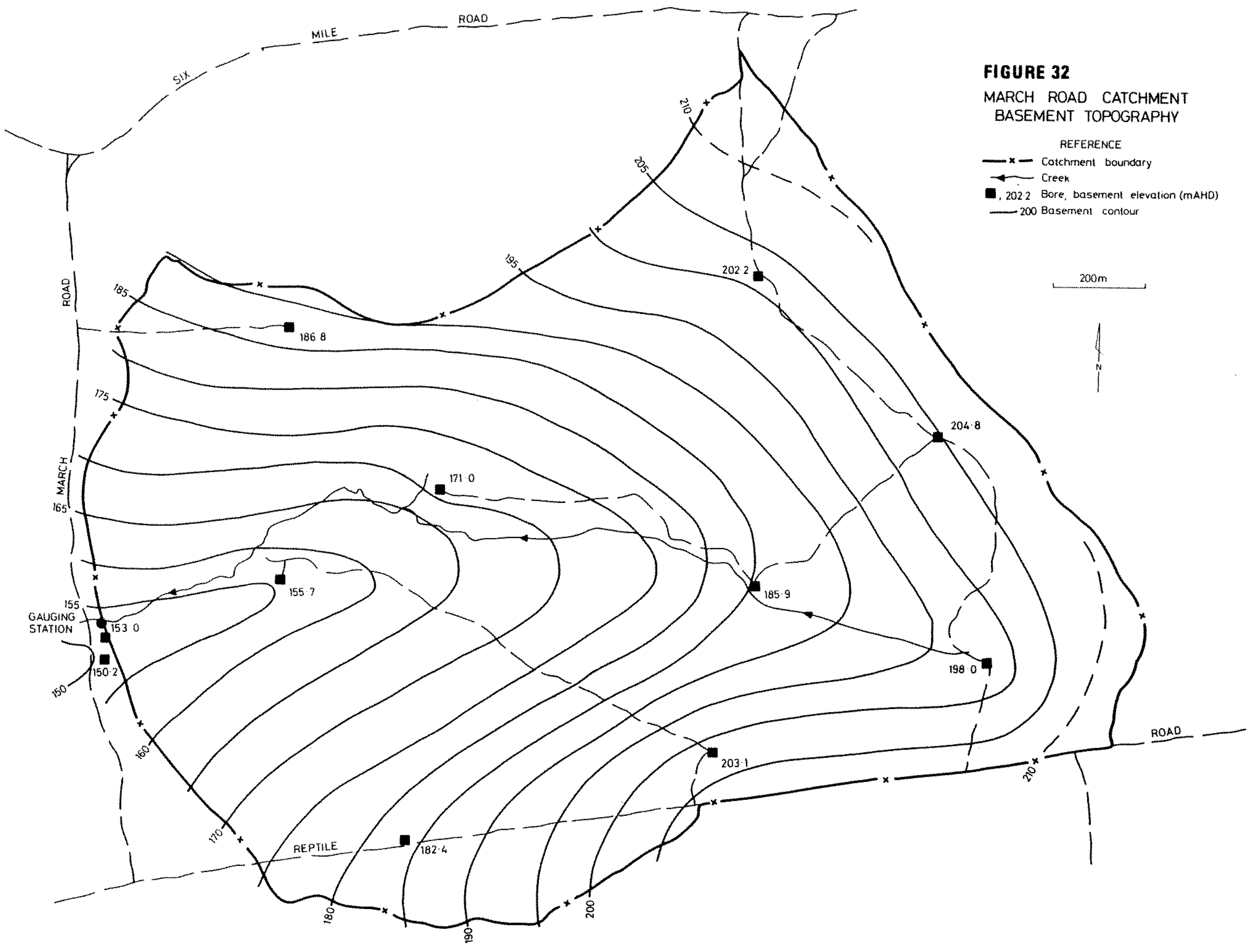
Catchment boundary
Creek
■ 10·2 (1·5) Bore, Depth to water (m) (Water level rise)
10 Depth to water contour (V.I. = 2 m)
Stream reserve

200 m

GSWA 23451

FIGURE 32

MARCH ROAD CATCHMENT BASEMENT TOPOGRAPHY



GSWA 23452

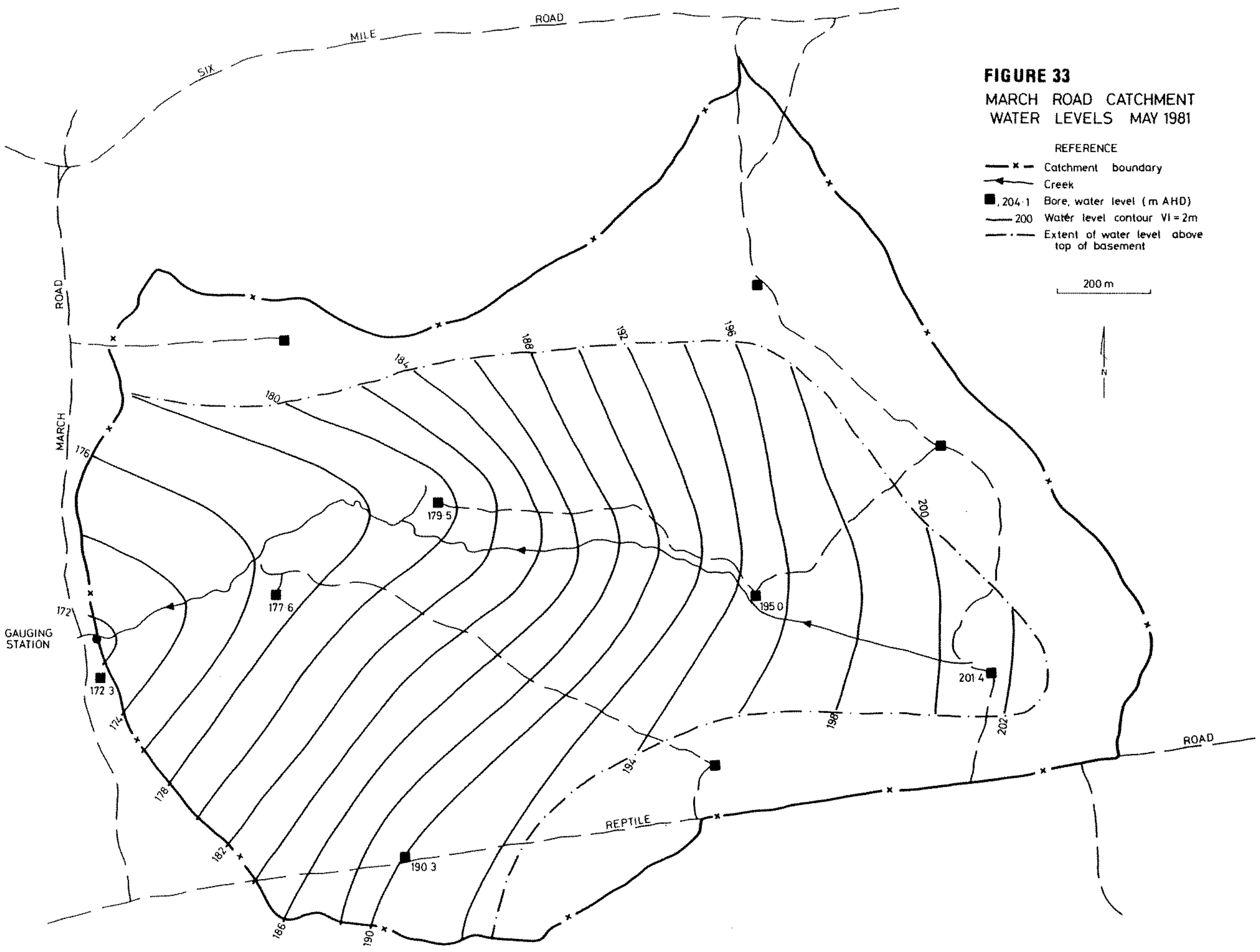


FIGURE 33

MARCH ROAD CATCHMENT WATER LEVELS MAY 1981

GSWA 23453

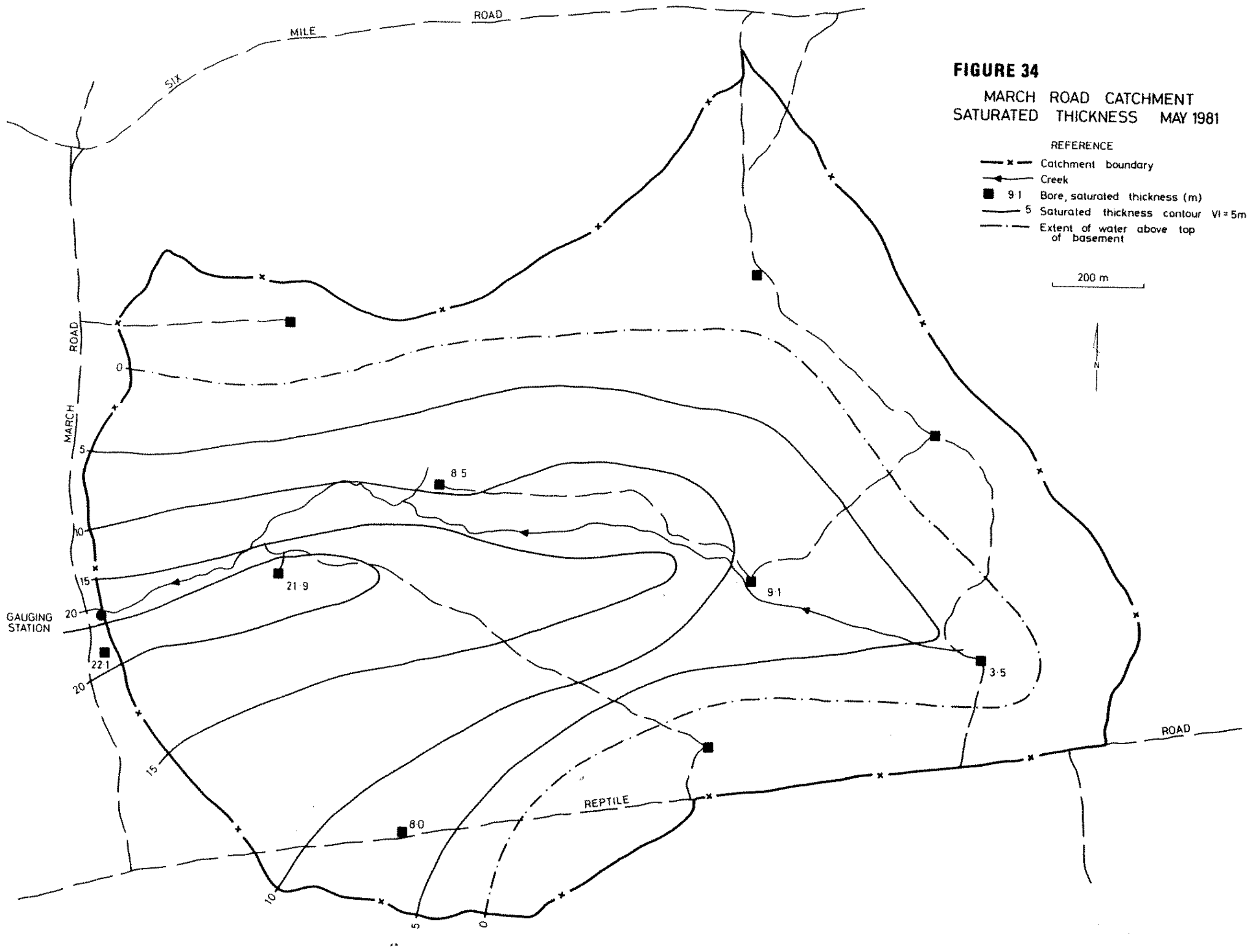


FIGURE 34
MARCH ROAD CATCHMENT
SATURATED THICKNESS MAY 1981

GSWA 23454

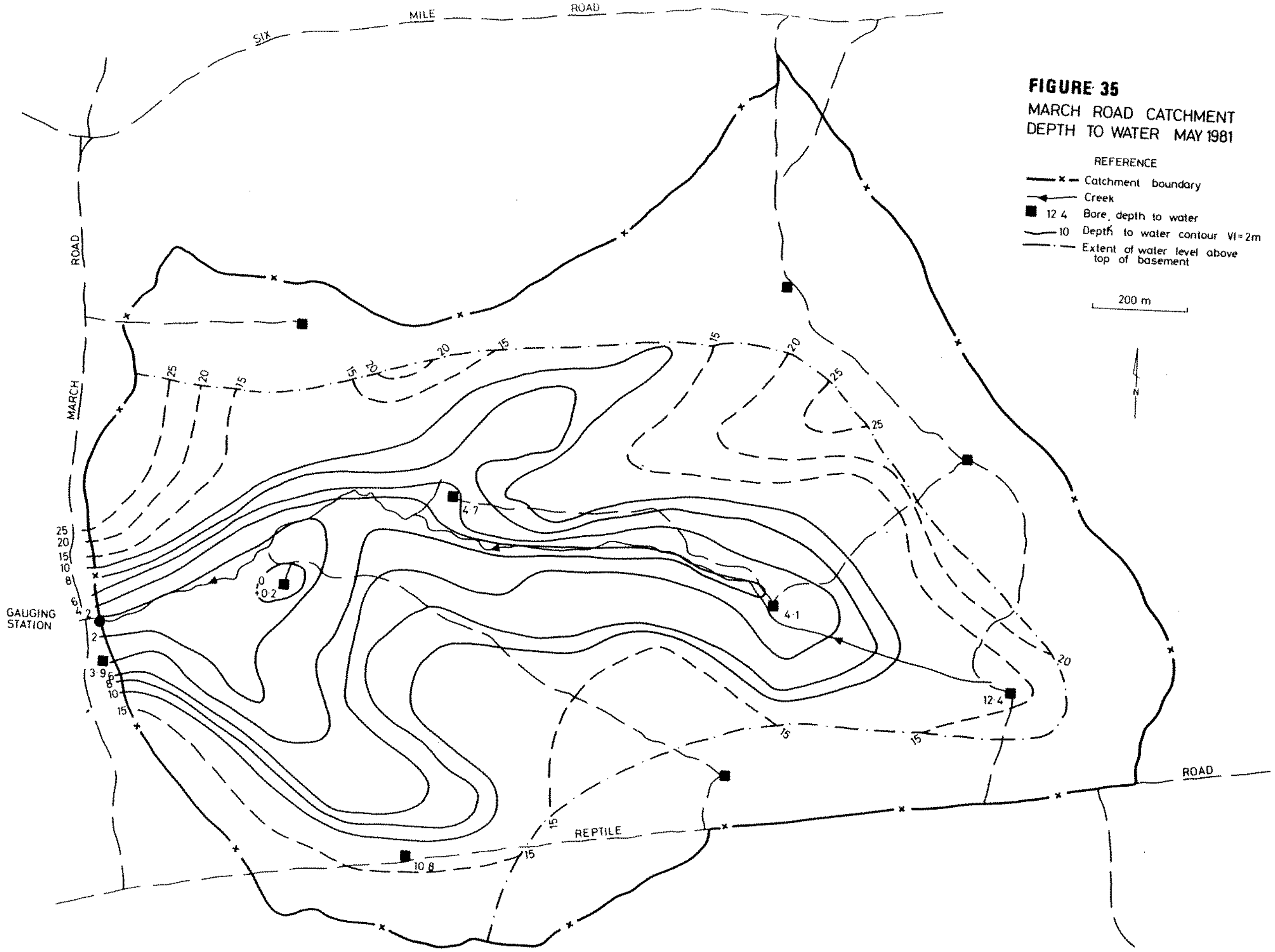


FIGURE 35
MARCH ROAD CATCHMENT
DEPTH TO WATER MAY 1981

GSWA 23455

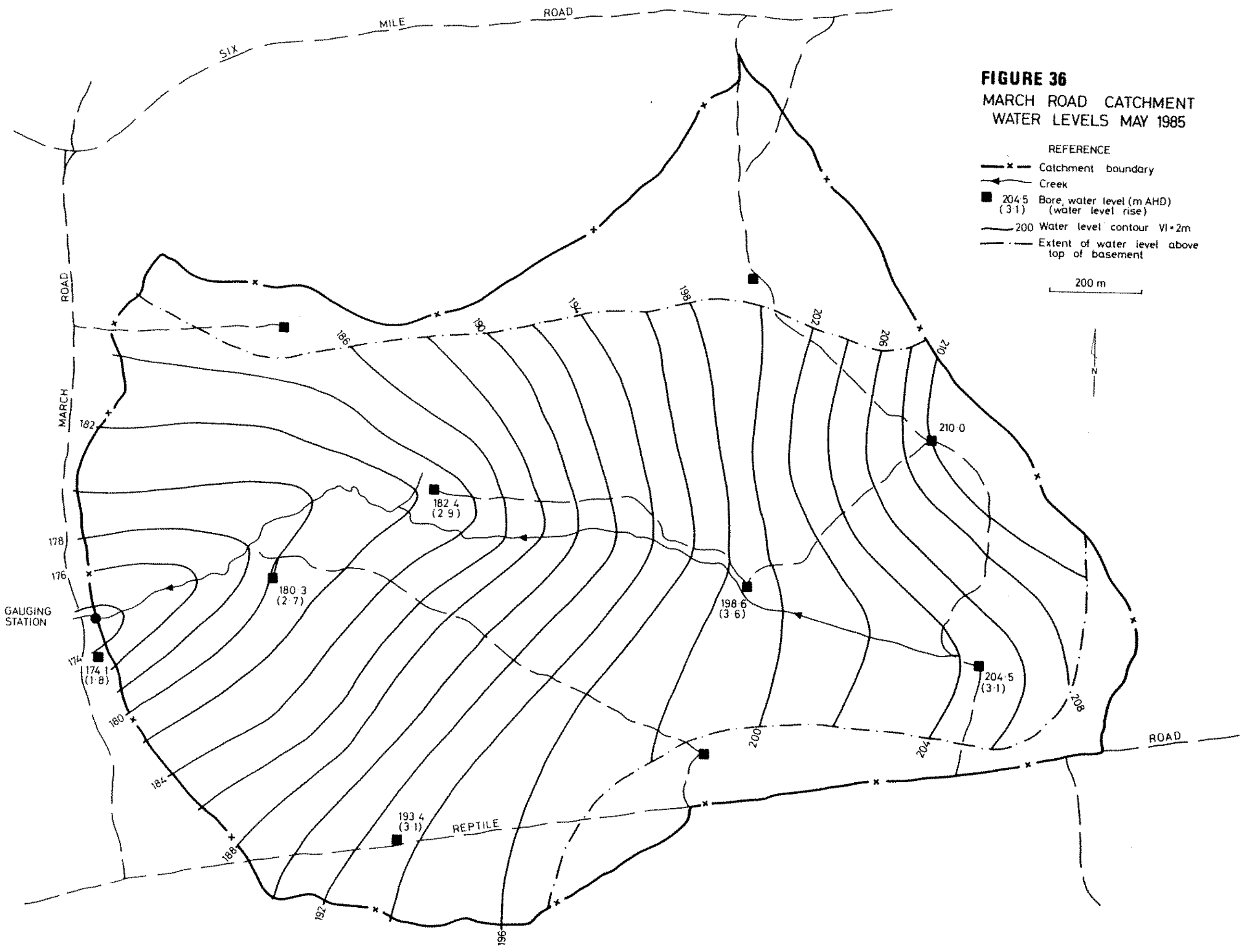
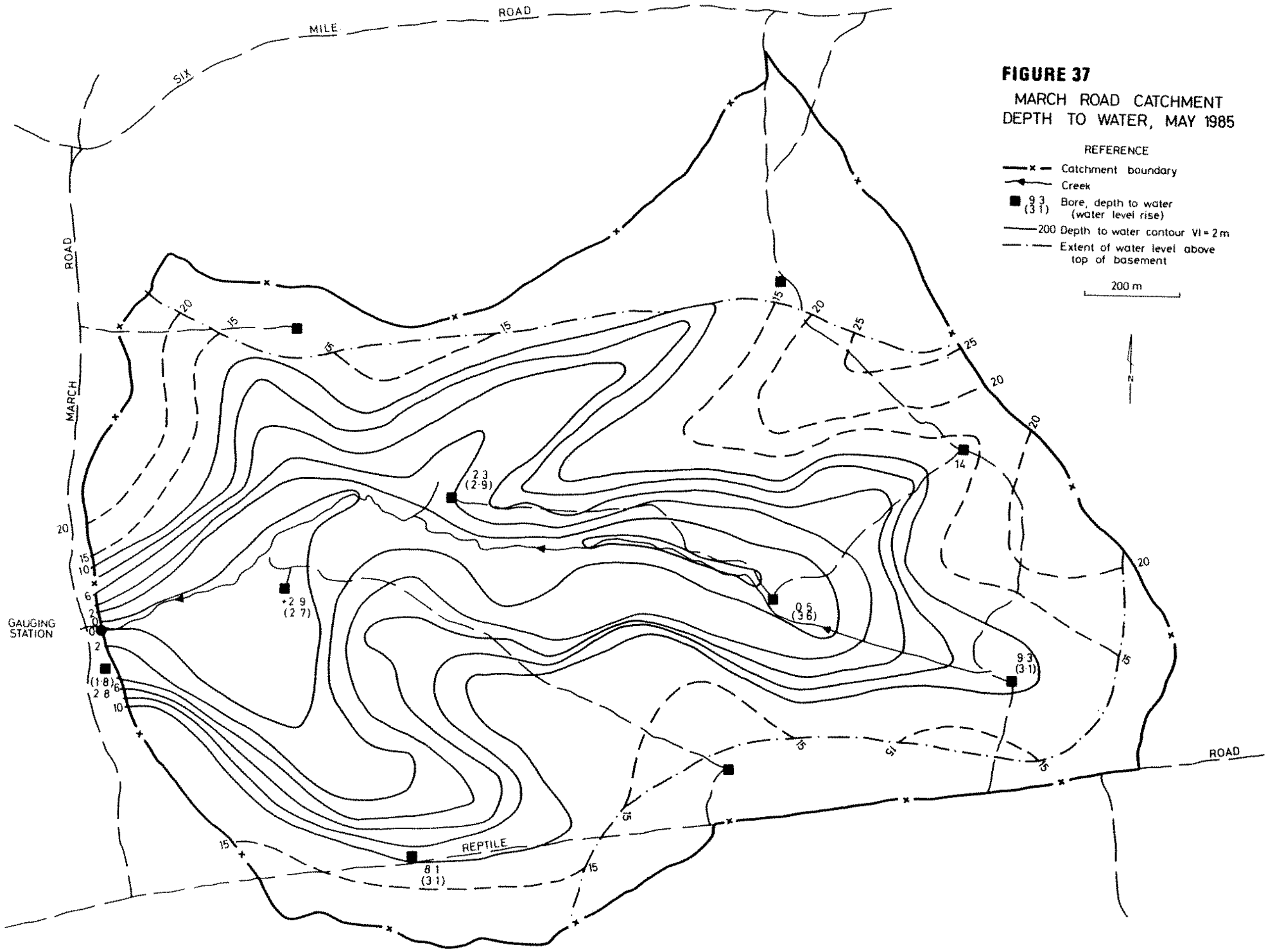


FIGURE 36
MARCH ROAD CATCHMENT
WATER LEVELS MAY 1985

GSWA 23456

FIGURE 37

MARCH ROAD CATCHMENT
DEPTH TO WATER, MAY 1985



GSWA 23457

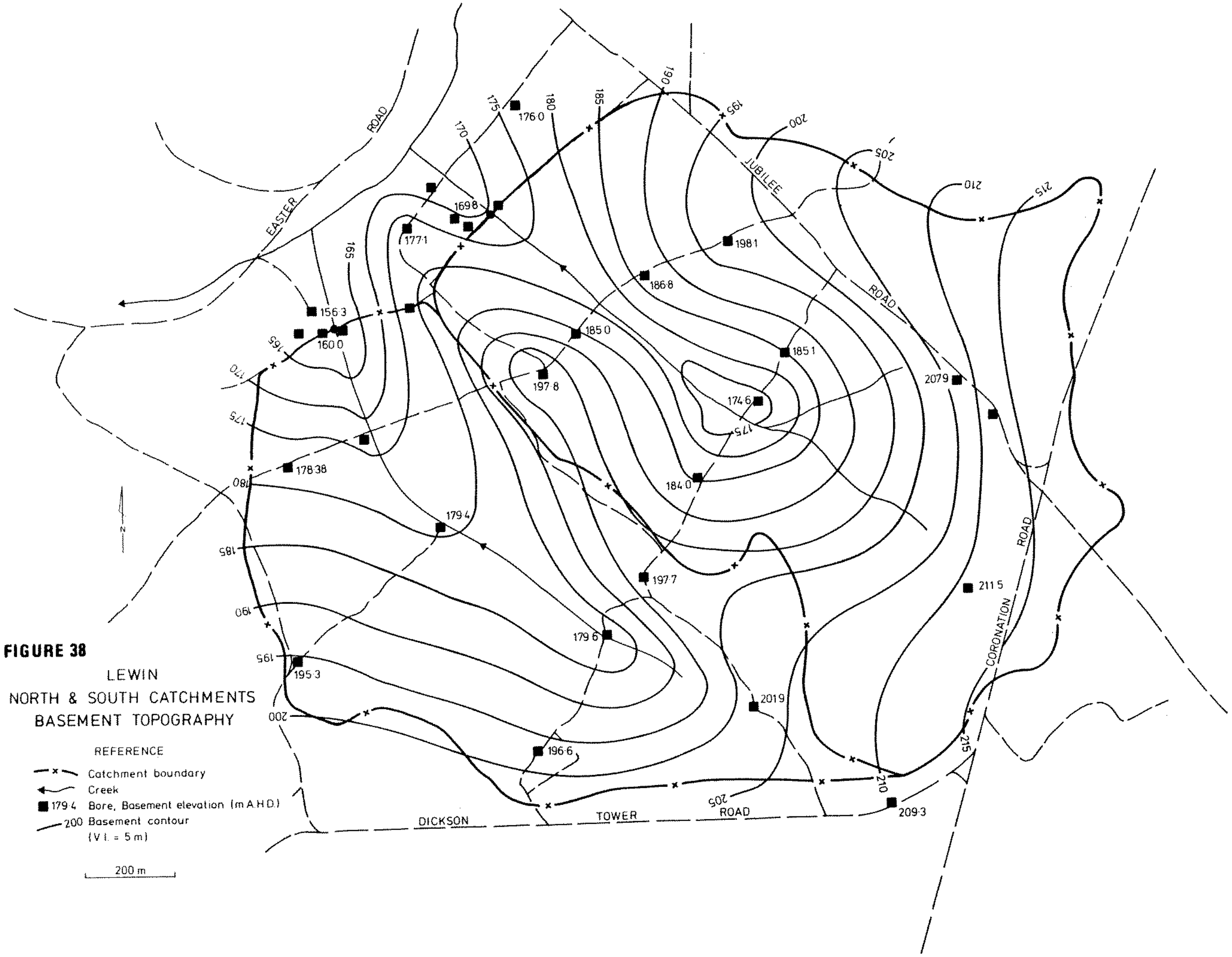


FIGURE 38

LEWIN
NORTH & SOUTH CATCHMENTS
BASEMENT TOPOGRAPHY

GSWA 23458

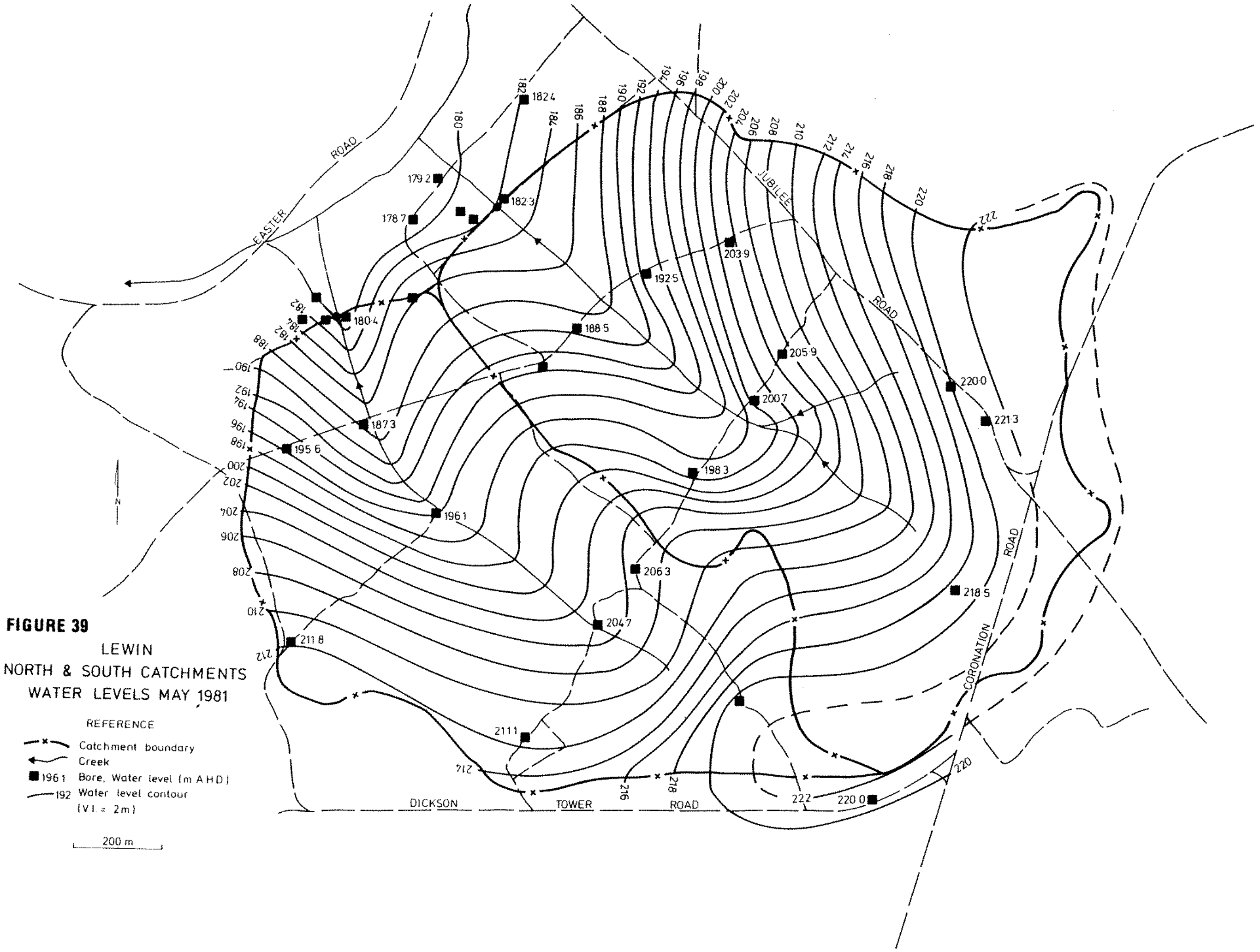


FIGURE 39

LEWIN
NORTH & SOUTH CATCHMENTS
WATER LEVELS MAY 1981

GSWA 23459

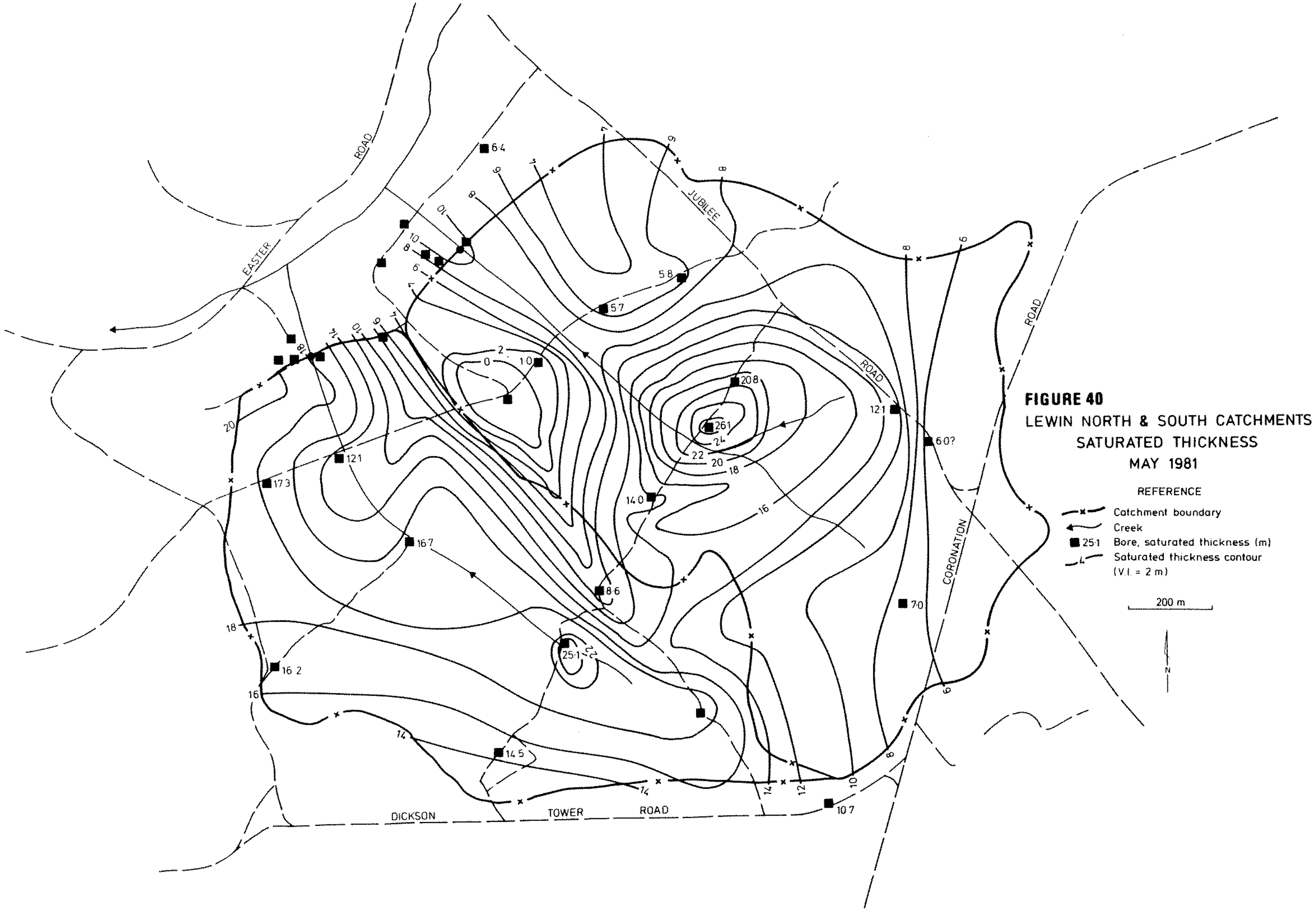


FIGURE 40
LEWIN NORTH & SOUTH CATCHMENTS
SATURATED THICKNESS
MAY 1981

GSWA 23460

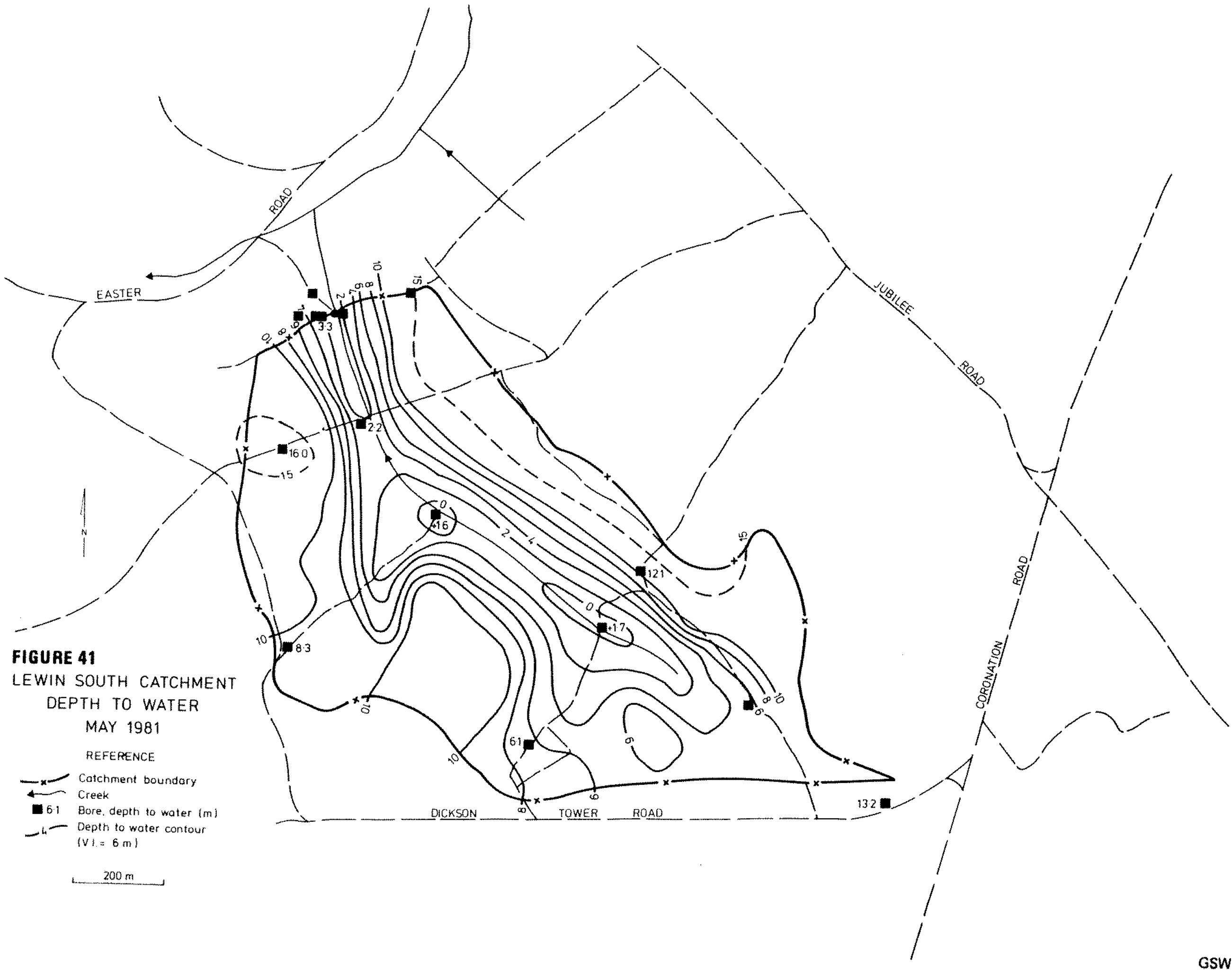


FIGURE 41
LEWIN SOUTH CATCHMENT
DEPTH TO WATER
MAY 1981

GSWA 23461

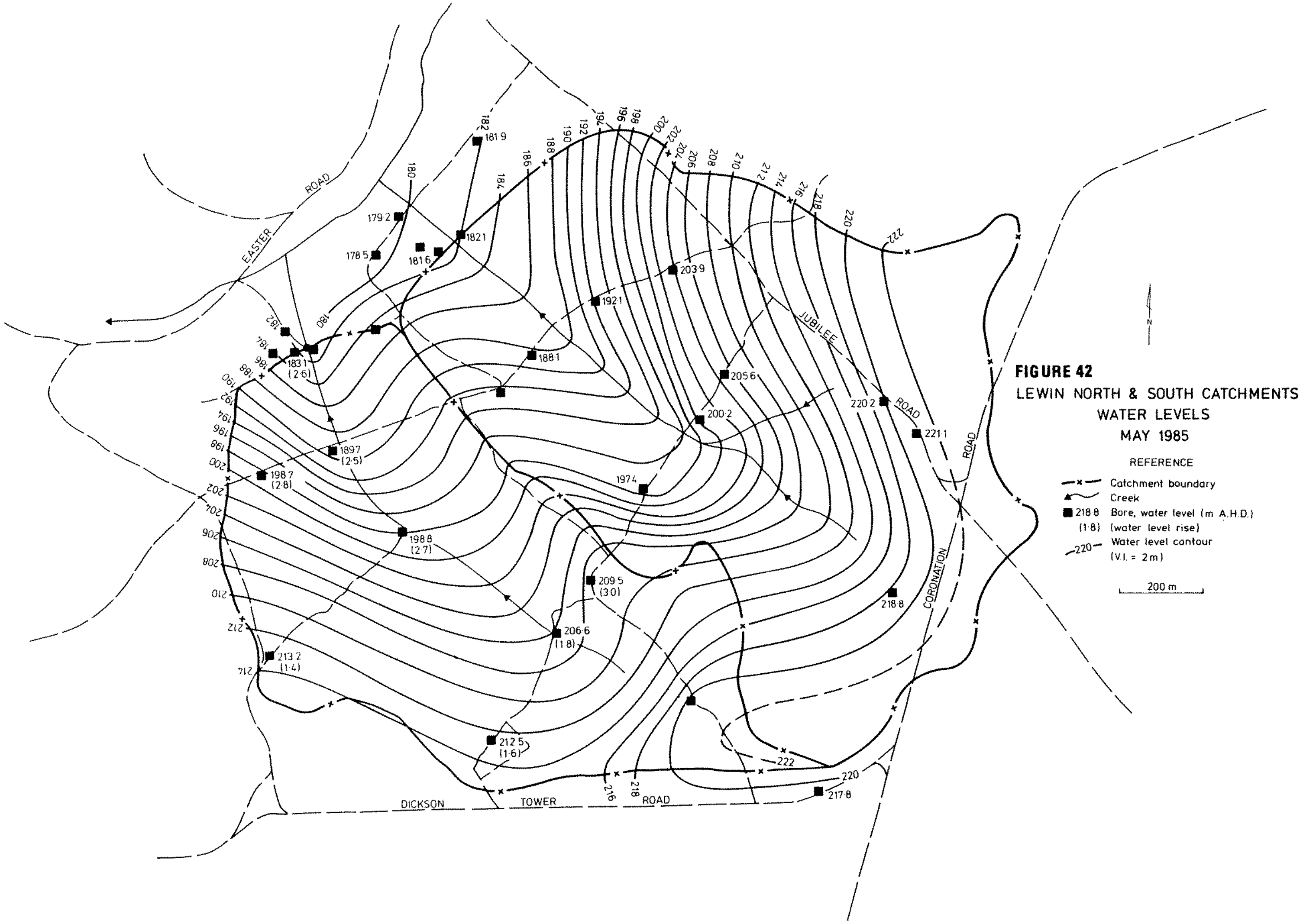


FIGURE 42
LEWIN NORTH & SOUTH CATCHMENTS WATER LEVELS MAY 1985

GSWA 23462

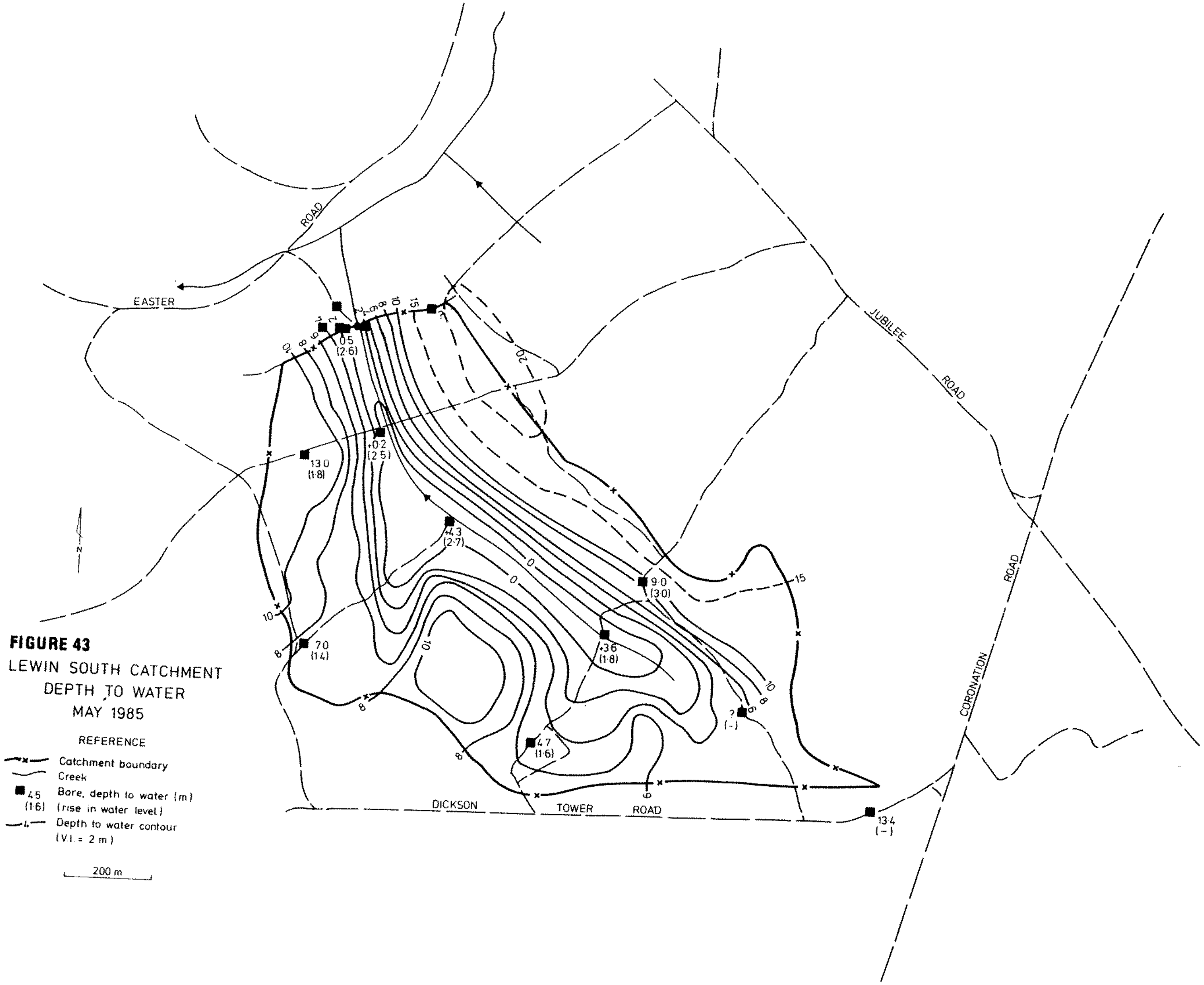


FIGURE 43
LEWIN SOUTH CATCHMENT
DEPTH TO WATER
MAY 1985

GSWA 23463