

Hydrogeology Report No. 1991/39

HYDROGEOLOGY OF THE ROBE RIVER
ALLUVIUM, ASHBURTON PLAIN,
CARNARVON BASIN

by

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ABSTRACT

Twenty-two exploratory bores were drilled into the alluvial aquifer along the Robe River on the coastal plain 80 km east of Onslow. The alluvial gravel consists of pebbles up to 100 mm diameter, is 3 km to 6 km wide, extends for 15 km along the river, and has a saturated thickness of as much as 13 m. The alluvium is Quaternary in age, and the gravel passes laterally into less permeable flood plain clay and silt. It rests unconformably on Proterozoic schist, Cretaceous conglomerate and siltstone, and Tertiary pisolite and limestone.

The aquifer is recharged directly through the river bed by periodic riverflow, and the groundwater salinity ranges from about 450 mg/L (similar to the flow weighted average river salinity of 398 mg/L) up to 1200 mg/L. Test pumping bores at four sites demonstrated bore yields ranging from 1000 to 3000 m³/d, and indicated a hydraulic conductivity of about 250 m/d which is supported by modelling. Estimates from changes in groundwater storage, based on the observed water table fluctuations, suggest that average recharge to the aquifer is about 12×10^6 m³ per year.

INTRODUCTION

LOCATION

The Robe River crosses the Ashburton Plain near Yarraloola Homestead in the Pilbara Region of Western Australia (Figure 1). The nearest towns are Pannawonnica, 50 km to the east, Onslow, 80 km to the west and Karratha, 150 km to the north east. The North West Coastal Highway crosses the Robe River 6 km upstream of the homestead and access to the area is provided by station tracks (Figure 2).

PURPOSE AND SCOPE

The Geological Survey of Western Australia has carried out a number of exploratory drilling projects to locate groundwater supplies for towns along the Pilbara coast. Alluvium along the Robe River was recognised as having potential for large supplies of potable groundwater and this report describes the results of the exploratory drilling and test pumping of the alluvium carried out between 1983 and 1985. The investigation was jointly funded by the State and Commonwealth Governments under the National Water Resources Assessment Program.

PREVIOUS INVESTIGATIONS

Following the discovery of large deposits of pisolitic iron ore in the Robe River valley, nineteen exploratory water bores to determine the availability of groundwater resources were drilled in 1965 for the Broken Hill Proprietary Company (BHP). The bores were drilled between 5 km and 10 km upstream from the present investigation area (Figure 1) and intersected a maximum thickness of 18 m of saturated alluvium. Bore yields

ranged up to 1000 m³/d, and the groundwater salinity was between 900 mg/L and 1400 mg/L TDS (milligrams per litre total dissolved solids).

The occurrence of low salinity groundwater in alluvium along the Robe River downstream from Yarraloola Homestead was subsequently recognised in a survey of pastoral bores and wells by Davidson (1975). Following his recommendations a seismic survey (Figure 2) was carried out to assess the thickness of alluvium, but the seismic refraction method could not distinguish the alluvium from the underlying sediments and seismic velocities were too high to indicate water-bearing material (Nowak, 1979).

In 1982 two bores were drilled for the State Energy Commission (SEC) near Yarraloola Homestead to provide water for hydrostatic testing of the Dampier-Perth natural gas pipeline (Rockwater, 1982). The bores yielded 1000 m³/d of water from the alluvium with a salinity of about 500 mg/L.

Artesian groundwater was encountered in the area in 1966-7 during a seismic survey for oil, when a deep shot hole at 77 m blew out with an oil-cut flow from the basal Cretaceous aquifer (Thomas, 1978). Subsequent exploratory drilling for oil and uranium has provided additional information on the Cretaceous aquifer (Muggeridge, 1978; Tyrwhitt and Sargeant, 1978). Allen (1987) in a review of the groundwater in the Carnarvon Basin has briefly described the groundwater resources in the area.

INVESTIGATION PROGRAM

The investigation consisted of drilling exploratory bores at twenty-two sites (Figure 2). Fifteen sites were drilled in 1983, and a further seven sites were drilled in 1984 to delineate the extent of the aquifer. Test pumping

bores and additional observation bores were drilled and tested in 1985.

The drilling was carried out by the Mines Department Drilling Branch using the mud-rotary drilling method. This method was found to be satisfactory, with only minor problems with loss of circulation where gravel was encountered.

The Robe Coastal Plain exploratory bores (prefix RCP) ranged from 18.5 m to 66 m deep but generally were about 30 m deep (Table 1). The aggregate depth drilled was 751 m. The shallow exploratory bores were 130 mm diameter and were cased with 80 mm PVC casing slotted over the water bearing interval. The deepest exploratory bore (RCP 5A) and the test pumping bores RCP 4P and RCP 10P were 200 mm diameter and cased with 155 mm diameter casing and in-line stainless test pumping sites (Table 2), *NOT Table 2*. previously drilled for the SE bore was drilled 20 m away from each pumping bore and constructed with 80 mm PVC casing slotted at the same depth as the screens in the pumping bore.

The strata were lithologically logged during drilling to enable differentiation of thin gravel beds, although samples were only retained at 3 m intervals. Gamma-ray logs were run in the cased bores after the completion of drilling in August 1984. Details of bore construction, strata and geophysical logs are in the bore completion reports (Commander, 1988).

On completion, the bores were developed by airlifting to obtain a clear water sample for chemical analysis by the Chemistry Centre of Western Australia.

TABLE 1 EXPLORATORY BORE DATA

Bore No.	Date	Elevation	Total	Slotted	Static	Salinity	Airlift
	Drilled	Casing top	Depth	Interval	Water	C' x 6.4	yield
		m AHD	m	m	level m	mg/L	m ³ /d
					12.11.85	TDS	
1	1.10.83	50.89	30	2-18	8.17	992	84
2	10-11.10.83	50.37	30	0-18	7.94	601	12
3	5.10.83	45.07	30	5.5-21.5	7.00	1011	27
4	11.10.83	49.09	36	5-35	8.47	902	144
5A	21-26.9.83	46.94	66	30-42	8.33	2086	6
5B	29.9.83	46.85	18.5	5-18	8.14	2259	8
6	6.10.83	41.71	23.5	5-23	7.15	1030	36
7	12-14.10.83	40.66	30	2-21	6.70	454	-
8	14.10.83	38.52	33	5-11	6.52	940	7
9	7.10.83	37.91	29	10-24	6.21	1068	62
10	21-22.10.83	36.50	30	5-10	7.13	716	-
				14-23			
11	20.10.83	34.34	24	5-16	6.61	755	-
12	15.10.83	32.10	30	5-11	6.57	723	14
13	19.10.83	29.20	27	5-14	5.52	704	86
				18-22			
14	18.10.83	29.25	29	5-13	6.34	672	48
15	17.10.83	27.94	35	5-14	6.51	684	86
16	29.8.84	49.30	28	13-23	6.57	800	247
17	22.8.84	43.89	29.5	5-29	8.77	1126	69
18	20.8.84	38.19	29.5	5-26	7.34	1286	69
19	17.8.84	29.49	32.5	20-30	6.37	3027	60
20	23.8.84	29.74	32.5	5-15	6.55	729	101
21	24.8.84	25.31	35.5	5-28	6.83	524	172
22	12.6.84	25.33	32.5	4-25	7.00	844	216
Camp bore	1-19.9.83	48.69	30	26-30	7.50	640	63

¹C = Electrical conductivity (mS/m @ 25°C)

Pumping tests, consisting of a six-stage step-drawdown test followed by an eight-hour constant-rate test at rates of 980 to 1340 m³/d, were carried out in RCP 4P, RCP 10P, SEC2-1 and SEC2-2 during October/ November 1985.

Water levels in the bores were monitored during the investigation period at intervals of between 2 weeks and 3 months, depending on river stage and access. The closer spaced measurements were made immediately following river flow. The Water Authority of Western Australia (WAWA) has undertaken monitoring in November each year from 1986 to the present. The bores have been levelled to Australian Height Datum (AHD).

ENVIRONMENT

PHYSIOGRAPHY AND VEGETATION

The investigation area lies on the Ashburton Plain (Hocking and others, 1987) which rises gently from the Cane-Robe tidal flats at the coast to about 50 m above sea level at the foot of an escarpment bordering the Nanutarra Region. The Robe River passes through a gap in the scarp and crosses the coastal plain in a narrow channel, or anastomosing channels, incised as much as 5 m below the general level of the plain. Several small shallow distributary channels run from above the river banks in a north-westerly direction, but carry water only at flood peaks.

The surface of the coastal plain is flat, and consists of a mosaic of stony plains and intervening areas of cracking clay soils (gilgai). The stony plains are covered with a shrub steppe dominated by snakewood (*Acacia xiphophylla*) whereas the gilgai is vegetated by mixed grasses (Beard, 1975). The river is flanked by a tree or shrub savannah of mixed grasses and scattered eucalypts,

and the banks are lined with river gums. The vegetation along the river banks becomes progressively thicker downstream from the investigation area, but terminates at a salt seep in Multhuwarra Pool (Figure 1). Much of the native vegetation has been denuded by sheep grazing in the last hundred years leaving large areas of bare soil.

CLIMATE

The region is arid with hot summers and warm winters. Rainfall is infrequent and intense; it usually results from tropical cyclones and thunderstorms between December and March, and from cold fronts between May and July. Very little rainfall is recorded in the months August, September and October. The average annual rainfall is about 290 mm, but the range is from zero to several times the average. Potential annual evaporation is about 2500 mm. Monthly rainfalls for the investigation period from Yarraloola Homestead and Pannawonnica are shown in Table 2.

TABLE 2: MONTHLY RAINFALL (mm) 1983-86

(Commonwealth Bureau of Meteorology)

Yarraloola Homestead (Sta. No. 5032)

Annual average: 293 mm

	J	F	M	A	M	J	J	A	S	O	N	D	TOT
1983	13	3	86	14	0	19	7	1	6	0	0	7	156
1984	31	73	79	23	223	0	36	4	10	0	0	12	491
1985	26	104	20	31	-	-	-	0	0	0	0	0	181*
1986	61	97	27	0	2	99	3	0	6	0	0	-	295*

Pannawonnica (Sta. No. 5069)

Annual average: 371 mm

	J	F	M	A	M	J	J	A	S	O	N	D	TOT
1983	14	9	137	20	0	16	24	1	7	0	50	37	315
1984	35	50	170	3	179	0	46	8	4	0	16	22	533
1985	28	31	25	51	3	6	34	0	0	3	0	0	181
1986	143	82	46	0	0	65	4	0	3	0	0	0	343

- no recording * incomplete record

RIVERFLOW

Riverflow in the Robe River has been measured at the Yarraloola gauging station since January 1972. The station is 4 km upstream from the investigation area (Figure 2) and measures runoff from a catchment area of 7250 km².

Runoff occurs only after heavy rain on the catchment, usually following cyclonic storms, and riverflows generally persist for about a month. Gauging records show an average of one riverflow event per year, but in the fifteen year period of records (Public Works Department, 1984; Water Authority of Western Australia, unpublished data) there were three years when the river flowed more than once, and three years with no flow at all (Figure 3).

Since 1972, annual flow has ranged from $8 \times 10^6 \text{ m}^3$ to $160 \times 10^6 \text{ m}^3$ with a mean of $51 \times 10^6 \text{ m}^3$. The median flow of the fourteen riverflows was $38 \times 10^6 \text{ m}^3$. Only the larger flows reach the sea, and none of the flows between 1976 and 1982 did so (M. Patterson, pers. comm., 1985)

The salinity of the river water has been measured intermittently since 1976 (WAWA, unpublished data). The salinity range was 107 mg/L to 1154 mg/L, and the flow weighted average to 1985 was 398 mg/L. The salinity measurements taken during riverflow following cyclone 'Chloë' in March 1984 are the most complete; they show that the salinity was about 120 mg/L at the flood peak, and thereafter increased steadily to about 550 mg/L (Figure 4).

During the investigation period there were three periods of riverflow: following cyclone 'Chloë' in March 1984, heavy rain in May 1984, and cyclone 'Gertie' in February 1985 (Figure 4). The shapes of the flood hydrographs are similar although there were subsidiary flows superimposed on the cyclone 'Gertie' flood.

GEOLOGY

SETTING

The investigation area lies on the boundary of the Phanerozoic Carnarvon Basin and the Precambrian Ashburton Basin. In this area the Peedamullah Shelf subdivision of the Carnarvon Basin (Hocking and others, 1987) contains Devonian-Carboniferous sedimentary rocks (not intersected in the drilling program) toward the coast, unconformably overlain by up to 200 m of gently northwest-dipping Cretaceous sediments. The Cretaceous sequence thins inland and extends on to the Proterozoic rocks of the Ashburton Basin on the inland margin of the Ashburton

Plain, and as a discontinuous capping in the Nanutarra Region (Figure 1).

Overlying the Cretaceous and Proterozoic rocks on the coastal plain are Tertiary and Quaternary sediments which reach a maximum thickness of 30m.

The stratigraphic succession of formations intersected by drilling is shown in Table 3.

TABLE 3: STRATIGRAPHIC SEQUENCE

AGE	FORMATION	THICKNESS (m) ¹	LITHOLOGY
Quaternary	Alluvium	30	Clay, gravel; (calcrete close to water table)
----- unconformity -----			
Tertiary Miocene	Trealla Limestone	17	Limestone, clay, marl
----- unconformity -----			
Eocene	Robe Pisolite	6	Pisolitic ironstone, silcrete, clay
----- unconformity -----			
Cretaceous	Toolonga Calcilutite	6	Clay, claystone
----- disconformity -----			
	Windalia Radiolarite	8?	Siltstone
	Muderong Shale	8?	Shale
	Yarraloola Conglomerate	23	Conglomerate, sand, clay
----- unconformity -----			
Proterozoic	Ashburton Formation	22	Schist

¹ Maximum thickness intersected during drilling

STRATIGRAPHY

Ashburton Formation

The Ashburton Formation (Williams, 1968) crops out in the hills on either side of the Robe River (Figure 1) and was encountered in bores in the southeast of the investigation area (Figures 5 & 6).

The formation consists of quartz-mica schist which is indurated in outcrop but weathered in the subsurface to a white to grey clay with sericitic feldspars and minor quartz.

The Ashburton Formation is of Proterozoic age (Williams, 1968) and is unconformably overlain by Palaeozoic, Cretaceous, Tertiary and Quaternary sedimentary rocks.

Yarraloola Conglomerate

The Yarraloola Conglomerate (Williams, 1968) crops out on the top of low hills near Yarraloola Homestead (Figure 1) and has been encountered in the subsurface in bores RCP 4, RCP 5A and RCP 17 (Figures 5 & 6).

The formation consists of pebble conglomerate with a white to yellow clay matrix, minor shale, and thin layers of pale grey sand. The pebbles are rounded white quartz, basalt, and tabular banded jaspilite, and range in size up to 100 mm diameter; the sand is composed of medium to coarse grained subangular clear and white quartz. The formation thickness ranges from about 3 m in RCP 17 to 22 m in RCP 5A.

The Yarraloola Conglomerate unconformably overlies an irregular topography on the underlying Proterozoic Ashburton Formation. It is Early Cretaceous in age and was deposited in a fluvial environment. The formation grades laterally into the Nanutarra Formation and Birdrong Sandstone (Hocking and van de Graaff, 1978).

Muderong Shale and Windalia Radiolarite

Dark green and dark blue to brown and black clay and siltstone which may belong to either the Muderong Shale or the Windalia Radiolarite (Condon, 1954) were encountered below the Cainozoic sequence in the central and eastern part of the area (Figures 5 & 6). A maximum thickness of 8 m was penetrated in RCP 11.

Samples were barren of palynomorphs and the sediments are correlated with the Early Cretaceous Muderong Shale or the Windalia Radiolarite on the basis of their lithology and stratigraphic position. Both formations are shallow marine deposits which conformably overlie the Nanutarra Formation.

Toolonga Calcilutite

In the north and west of the area yellow and light green to white clay with thin bands of claystone or marly limestone was encountered at the base of the Cainozoic sequence (Figures 5 & 6). This is correlated with the Late Cretaceous Toolonga Calcilutite (Johnston and others, 1958), and a maximum thickness of 6 m was penetrated in RCP 12. A blueish green colouration at the top of the sequence is interpreted to be due to weathering. The Toolonga Calcilutite disconformably overlies the Windalia Radiolarite.

Robe Pisolite

The Robe Pisolite (de la Hunty, 1965) crops out in the Robe River valley (Figure 1) and is present beneath the coastal plain to the southwest near Warramboo (Williams, 1968). In the investigation area the formation is preserved in the subsurface on either side of the present course of the river (Figure 6).

In outcrop the formation consists of pisolitic and massive iron oxides with detrital material, fossil wood and seams of clay. In the Robe River coastal plain bores the formation consists of red-brown and black pisolitic ironstone, yellow clay and mottled red and yellow vitreous silcrete. The formation is 7 m thick at RCP 18 and RCP 19, where it directly overlies Cretaceous rocks. The Robe Pisolite is a fluvial deposit, probably of Late Eocene age, and may have been subjected to lateritization and silicification in the Oligocene (Hocking and others, 1987).

Trealla Limestone

Limestone and clay in the centre of the investigation area are assigned to the Trealla Limestone which extends over much of the coastal plain (Hocking and others, 1987). The formation ranges from a finely crystalline limestone to a pale cream and yellow clay, often with a greenish tinge. Dendritic manganese is common on broken surfaces of the limestone. The maximum thickness encountered was 17 m in RCP 4, where the limestone is indurated, but elsewhere in the area the formation appears to have been eroded and is less than 10 m thick. The formation unconformably overlies Cretaceous and older Tertiary sediments and is unconformably overlain by Quaternary alluvium.

The Trealla Limestone is a marine or lagoonal deposit of Middle Miocene age (Hocking and others, 1987). The limestone is similar in lithology to the Millstream Dolomite (Barnett and Commander, 1986) which bears the same stratigraphic relationship to the Robe Pisolite in the headwaters of the Robe River 90 km to the east.

Robe River alluvium

Flood deposits of the Robe River as much as 30 m thick cover the coastal plain and form a delta at the mouth of the river. On the coastal plain the sediments are mainly overbank deposits of clay and silt. Gravel bed-load deposits crop out in the river bed, and occur in the subsurface within 3 km of the river where they are concealed by the overbank deposits.

The gravel in the river bed consists of rounded, tabular pebbles, up to 100 mm diameter and 50 mm thick, of banded chert and jaspilite together with rounded pebbles of basalt and quartz. The chert, jaspilite, and basalt are derived from Archaean or Lower Proterozoic rocks of the Hamersley Basin which crop out in the upper reaches of the catchment 40 km upstream, and are also reworked from the Yarraloola Conglomerate. The gravel is generally loose and unconsolidated, but some surface cementation can be seen near semi-permanent river pools.

At RCP 10 the gravel between 10 m and 23 m is conspicuously different from the overlying material in having weathered and coated surfaces on the pebbles, which suggests they are a considerably older deposit.

The gravel is thickest (15 m) close to the present river course at Yarraloola Homestead. It thins laterally, away from the river, and progressively downstream where it is interbedded with clay. At RCP 21 and 22, at the northern end of the area, individual gravel beds are less than 3.5m thick.

The clay and silt are generally red-brown and indurated with occasional thin layers of fine pebbles and grains of jaspilite and basalt.

Pisolitic ironstone, probably derived from the Robe Pisolite, is present at the base of the gravel sequence in RCP 17 and 18, and also within the clay in RCP 12. Bright blue clay at the base of the gravel in RCP 9 (overlying Trealla Limestone) appears to have been derived from erosion of Cretaceous sediments.

Extensive development of calcrete within the alluvium has taken place by hydrochemical action. The calcrete is commonly developed close to the water table and to a depth of 5 m below the water table. A complete series from slightly calcareous clay, through white to pink clay with calcite veining, to finely crystalline calcrete can be seen in the borehole samples. The gravel is generally unaffected but at RCP 10 deposits of crystalline calcite in concentric rings, up to an aggregate thickness of 2 mm, were observed on pebbles between a depth of 13 m and 14 m. The finely crystalline calcrete is similar to the limestone in RCP 4 which was correlated with the Tertiary Trealla Limestone on the basis of its thickness and uniform lithology.

The alluvium is part of an alluvial fan deposited by the Robe River where it discharges onto the Ashburton Plain. The Robe River alluvium coalesces with more clayey deposits of adjacent small drainage lines. It unconformably overlies an irregular topography on Proterozoic, Cretaceous, and Tertiary rocks, and is considered to be of Quaternary age. The alluvium is being periodically reworked by river floods.

HYDROGEOLOGY

ROBE RIVER ALLUVIUM

Extent

The gravel (bed-load) component of the Robe River alluvium is a major aquifer. The aquifer grades laterally and is bounded by the flood plain silts and clays, which have a very much lower transmissivity.

The gravel is thickest and deepest adjacent to the Robe River (Figure 7). The thickest saturated section of gravel penetrated by the drilling is an aggregate of 13 m at RCP 10. The aquifer thins away from the river and towards the downstream end of the investigation area, where individual gravel beds only a few metres thick become progressively intercalated with clay (section AA' in Figure 5). The gravel is exposed only in the river bed, and elsewhere it is covered at the surface by between 2 m and 5 m of overbank silt.

The alluvial gravels overlies relatively impermeable Tertiary, Cretaceous and Proterozoic rocks. The Trealla Limestone is mostly clayey and impermeable, except in one bore where it is fissured limestone. The Robe Pisolite has a low permeability in this area, although elsewhere it is a highly transmissive aquifer (Barnett and Commander, 1986). The Toolonga Calcilutite, Windalia Radiolarite, Muderong Shale and Ashburton Formation also form an impermeable base to the alluvial aquifer. Some downwards leakage may take place into the Yarraloola Conglomerate, but this is considered to be small.

Water table configuration

The water table is generally between 5 m and 9 m below ground level (Figure 8), but it is subject to seasonal and annual fluctuations of as much as 4.5 m in bores close to the river (Figure 9).

The water table slopes north westwards from about 43 m where the Robe River enters the coastal plain to 18 m AHD in the north west of the area (Figure 8). The water table also slopes away from the river, depending on the time elapsed since riverflow.

The gravel is only partially saturated, and throughout the area, especially to the west of the river, several metres of unsaturated gravel occur above the highest observed water table level (Figure 5).

Recharge

Recharge to the alluvial gravels takes place by direct infiltration through the river bed during periods of river flow. The amount of recharge is controlled by the frequency, size and duration of river flows.

The response of the water table to recharge from river flows during the period 1983-6 is shown on Figures 9, 10A and 10B. Close to the river, the water table rises rapidly during a flow event; with increasing distance from the river, the response is delayed and reduced. Water levels in RCP 5 and RCP 19 which are beyond the boundary of the gravel in alluvial silt and clay show little or no response to the river flow in the period 1983-6. The area of riverine recharge is therefore limited to the area of alluvial gravel, and the flood plain silts are likely to be recharged mainly by local rainfall and runoff.

During the investigation period the river flowed on three occasions (Figures 3 & 4): twice in 1984 and once in 1985. The recharge to the aquifer resulting from these flows can be estimated from the volumetric change between the water table level before and after flow (Figure 10A, B), using an assumed specific yield of 0.1. Water levels used are measured values in the bores, except for the pre-flow levels in January 1984 which have been extrapolated from measurements made the previous year. The differences in water table levels were contoured and the volumes calculated from areal measurement.

The calculated recharge (Table 4) does not account for the groundwater outflow during the period, and is therefore an underestimate.

TABLE 4: CALCULATED RECHARGE IN 1984 & 1985

Period of water table rise	Recharge ($\times 10^6 \text{ m}^3$)
24 Feb. - 24 July 1984	24
30 Jan. - 3 Apr. 1985	10

Water table levels in bores close to the river reached a slightly higher elevation (Figure 9) following the 1985 flow, owing to the higher pre-flow water table level, and to the longer duration of flow.

Storage

The total groundwater storage in the alluvial gravel can be calculated from the volume of saturated aquifer multiplied by the specific yield. The volume of saturated gravel on 12 November 1985, within the boundaries shown on Figure 7, has been estimated by measuring the area within each isopach of aggregate thickness, and multiplying by the average thickness. The volumes of groundwater in

storage have been estimated by using an assumed specific yield of 0.1, and are given in Table 5.

TABLE 5: GROUNDWATER STORAGE

Isopach interval (m)	Average thickness (m)	Area (km ²)	Volume* (x10 ⁶ m ³)
0-5	2.5	56	14
5-10	7.5	48	36
>10	10	20	20
Total			70

*specific yield of 0.1

The annual change in storage during the investigation period can be calculated in the same way as above from the change in water table level taken for convenience from November to October of the subsequent year (Table 6).

TABLE 6: ANNUAL CHANGE IN STORAGE

Period	Change in Storage*(x10 ⁶ m ³)
Nov. 1983 - Oct. 1984	+ 16
Nov. 1984 - Oct. 1985	- 2
Nov. 1985 - Oct. 1986	- 12

*specific yield of 0.1

Historical water level changes

Water table levels have been measured in station wells (Figure 2) at intervals since 1964, and data from selected wells are given in Table 7. They show an approximate correlation with river flow (Figure 3), being relatively high following the large flow of 1974, and low in 1979 and 1983. The lowest levels were measured at the end of 1983 following the longest period without river flow since 1972.

TABLE 7: HISTORICAL WATER LEVELS IN STATION WELLS*
(m below surface reference point)

	10.10.64	22.6.74	9.11.79	5.10.83	29.8.84
Eve Well	5.5	4.40	6.80	7.46	6.00
Peter Well	6.4	5.70	-	8.18	6.85
Daisy Well	4.9	4.80	7.30	8.12	5.80
Princess Well	8.2	7.30	9.75	-	8.50
Queen Well	7.3	5.15	7.05	7.30	-

* from GSWA records

Hydraulic conductivity

RCP 10P and the two SEC pumping bores in the gravel aquifer were pumped at rates of 980 to 1340 m³/d with 1.1 m to 4.4 m of drawdown (Table 8). Drawdowns in the observation bores, located 20 m from the pumping bores, ranged from 0.25 m to 0.29 m, and gave transmissivities, derived from matching time-drawdown data to non-equilibrium type curves, of 1300-4900 m²/d.

TABLE 8: TEST PUMPING DATA

Pump bore					Observation bore 20m			
Bore	Pump rate m ³ /d	Drawdn. (8hrs) m	Sp.cap (8 hrs) m ² /d	Sp.cap (30 min) m ² /d*	Drawdn. (8hrs) m	T m ² /d	b m	K m/d
RCP4P	980	4.4	220	2000	0.29	3500	16	220
RCP10P	1320	3.3	400	1250	0.29	1300	9	150
SEC2-1	1170	2.8	420	1250	0.25	3100	12	260
SEC2-2	1340	1.1	1200	2500	0.26	4900	12	400

Drawdn = drawdown; Sp.cap = specific capacity;
T = transmissivity; b = aquifer thickness;
K = hydraulic conductivity

* Calculated according to the method of Sheahan (1971)

Estimates of hydraulic conductivity in the Robe River alluvium, derived from the pumping tests (Table 8), ranged from 150 m/d in partially cemented gravel at RCP 10 to 260

and 400 m/d in clean gravel at SEC2-1 and SEC2-2 respectively.

The hydraulic conductivity can also be estimated by modelling the response of the water table to river flow, assuming the aquifer is of constant thickness. Observed water level rises, thirty days after the first river flow in March 1984, were plotted against distance from the river (Figure 11). The best fit curve to these data points was obtained from the equation given by (Gill, 1985):

$$\frac{S}{S_0} = \frac{4}{\pi} \sum_{n=1,3,5..}^{\infty} \frac{1}{n} \exp - \left[\frac{k}{N} n^2 \pi^2 \frac{t(H_0-S_0)}{4L^2} \right] \sin \left[\frac{n\pi x}{2L} \right]$$

where:

S_0 is the rise in water table at the river (3.75 m)
 S_0-S is the water table rise (m) at a distance
 x (m) from the river
 H_0 is the final saturated thickness of the aquifer at the river (12 m)
 L is the width of the aquifer (2000 m)
 t is the time elapsed since river flow commenced (30 days)
 $\frac{k}{N}$ is the ratio of the hydraulic conductivity (k in m/d) to the specific yield (N assumed = 0.1),

yielding a hydraulic conductivity of 250 m/d.

The derived hydraulic conductivity from the seven bores up to 1.6 km from the river is in broad agreement with the values derived from pumping tests, even though the pumping tests apply to a small part of the aquifer close to the pumped bore.

Groundwater flow

Groundwater in the alluvial gravels flows in a general northwesterly direction, approximately parallel to the river (Figure 8). When the river flows, a groundwater

mound builds up beneath the river bed as recharge occurs to the shallow gravels flanking the river (Figure 12A), and the mound subsides when the river ceases to flow (Figure 12B).

The volume of groundwater flow, Q , can be estimated from the Darcy equation:

$$Q = kbi l$$

where:

- k is hydraulic conductivity (m/d)
- b is aquifer thickness (m)
- i is hydraulic gradient (dimensionless)
- l is cross section width (m)

The average annual groundwater throughflow in the alluvial gravel across sections A-F and G-J, based on the water table configuration in November 1985 (Figure 8), is similar. Depending on the value of hydraulic conductivity (k) this ranges from an average of $2.9 \times 10^6 \text{ m}^3$ to $7.6 \times 10^6 \text{ m}^3$ (Table 9).

TABLE 9: THROUGHFLOW CALCULATIONS

SECTION	AQUIFER THICKNESS m	HYDRAULIC GRADIENT $\times 10^{-3}$	LENGTH m	ANNUAL THROUGHFLOW $\text{m}^3 \times 10^6$	
				$k=150\text{m/d}$	$k=400\text{m/d}$
A - B	3	1.4	1000	0.23	0.6
B - C	7.5	1.2	1500	0.74	2.0
C - D	11	1.1	1700	1.1	3.0
D - E	7.5	1.2	1500	0.74	2.0
E - F	2.5	1.6	500	<u>0.1</u>	<u>0.3</u>
A - F total				2.9	7.9
G - H	2.5	1.4	3500	0.67	1.8
H - I	7	1.2	4300	2.0	5.3
I - J	2.5	0.8	800	<u>0.1</u>	<u>0.2</u>
G - J total				2.8	7.3

Discharge

The average annual discharge from the aquifer can be equated to the decline in storage in a year with no recharge. Between November 1985 and October 1986 there was no river flow and the annual storage depletion (Table 6) was estimated to be $12 \times 10^6 \text{ m}^3$ (using a specific yield of 0.1). This decline in storage is accounted for by groundwater flow out of the area and by evapotranspiration within the area.

Discharge from the alluvial gravels occurs downstream of the investigation area by transpiration from thick vegetation which occupies the river bed for 10 km upstream of the saline seep at Multhuwarra Pool.

Water loss from this vegetation can be estimated by assuming that annual transpiration is 80% of the pan evaporation, approximately 2 m. The total annual water loss from an area 10 km long and 200 m wide is therefore about $4 \times 10^6 \text{ m}^3$.

Discharge to the northwest of the investigation area is indicated by the presence there of low salinity groundwater (Figure 13). However, the vegetation is sparse in this area and it is likely that discharge occurs from the water table by evaporation through the unsaturated zone at a relatively low rate over a large area.

Groundwater model

A groundwater flow model of the alluvial gravels was constructed to assist in the determination of hydraulic conductivity, specific yield and recharge. The modelling was carried out by S.J. Appleyard using the United States Geological Survey MODFLOW finite difference groundwater flow model (McDonald and Harbaugh, 1984). A one-layer

model consisting of $228 \times 1 \text{ km}^2$ cells was used. The model dimensions were based on the extent and saturated thickness of the aquifer given in Figure 7. A constant flux boundary at the input end, and a constant head boundary at the output end were used to simulate groundwater inflow to and outflow from the model, and no-flow boundary conditions were used to simulate the outer limits of the aquifer. River flow was simulated with the river leakage package of the model.

Calibration of the model was carried out using 1985 water-level and river-flow data, where a large flow event was followed by a long water-level recession. A good fit between simulated and actual water levels was obtained using a hydraulic conductivity of 200 m/d and a specific yield of 0.15 for the aquifer (Figures 14 & 15). The simulation indicated that recharge to the aquifer in 1985 was about $8 \times 10^6 \text{ m}^3$, which agrees well with the value of $10 \times 10^6 \text{ m}^3$ previously estimated by the analysis of hydrographs (although in the latter a specific yield of 0.1 was used). The simulation also gave a groundwater throughflow of about $5 \times 10^6 \text{ m}^3$, within the range indicated in Table 9.

Salinity

The regional groundwater salinity pattern in the alluvial deposits of the coastal plain shows a lobe of low salinity groundwater around the Robe River (Figure 13). The groundwater salinity in the Robe Coastal Plain bores drilled in this lobe ranges from 454 mg/L to 3027 mg/L (Figure 16).

In the alluvial gravels the groundwater salinity ranges from 454 mg/L near the river to 1280 mg/L at the margin. The groundwater salinity is directly related to the salinity of the recharge water from the river, and

increases at the edge of the aquifer due to mixing with higher salinity water from the flood plain deposits.

The lobe of low salinity groundwater extends north-westwards from the river in the direction of groundwater flow (Figure 13). The lowest salinity groundwater occurs at RCP 7, where it is almost the same as the weighted average salinity of 398 mg/L of the river flows (Public Works Department, 1984). On the eastern side of the river, the groundwater salinity is generally higher than on the western side, and ranges up to nearly 1300 mg/L (RCP18).

The groundwater salinity in the Robe River alluvium generally decreases with depth below the water table. This is shown by comparison of the groundwater salinity in shallow station wells and bores with that in the deeper exploratory bores (Figure 16), and is believed to be due to evapotranspiration.

Periodic sampling of the station wells in the area revealed little variation in salinity during the investigation period, except in Tragedy Corner Bore (Table 10). This bore is unusual both for its high salinity compared with nearby exploratory bores RCP 13, 14 and 22, and for its salinity variation from 1400 - 4500 mg/L. The more saline readings were obtained following river flows when water levels were high, and the salinity decreased thereafter as water levels declined.

**TABLE 10: SALINITY VARIATION IN TRAGEDY CORNER BORE
1983-85**

(mg/L TDS, by conductivity)						
1983	1984		1985			
5 OCT	29 AUG	8 DEC	22 FEB	3 APR	7 MAY	12 NOV
1400	3700	2300	1700	4500	4200	2100

Hydrochemistry

The groundwater in the Robe Coastal Plain bores shows a progressive enrichment of sodium chloride at the expense of calcium and bicarbonate with increasing total salinity (Figure 17). Evidence of calcrete formation close to the water table suggests that calcium bicarbonate is removed by precipitation. There is also a slight decrease in magnesium and an increase in the sulphate proportion with increasing salinity.

The groundwater is hard to very hard, ranging from 250 to 470 mg/L total hardness (Table 11). Nitrate is present at concentrations ranging up to 12 mg/L, and fluoride ranges from 0.3 to 1.6 mg/L. In potable groundwater (with a salinity of less than 1000 mg/L), there is a maximum nitrate content of 6 mg/L and a maximum fluoride content of 1.1 mg/L. Boron ranges in concentration from 0.2 to 0.7 mg/L and silica concentrations are generally in the range 45 to 65 mg/L. Iron was analysed only in the non-aerated samples from pumped bores and was present in concentrations less than 0.13 mg/L (Table 11).

Temperature

The temperature of groundwater measured during the pumping tests was 31.5°C.

TABLE 11 CHEMICAL ANALYSES OF GROUNDWATERS

						Mineral matter in mg/L																
Bore Name	Sample No	Lab No	Sample Date	pH	Conductivity msm @ 25°C	TDS	Total Hardness	Total Alkalinity	Ca	Mg	Na	K	CO ₃	HCO ₃	Cl	SO ₄	NO ₃	SiO ₂	B	F	Fe	
						(180° by calc)	(CaCO ₃)	(CaCO ₃)														
RCP1A	65662	83W	9820	7.10.83	8.0	155	855	390	57	60	163	12	<2	348	262	83	<1	44	0.49	0.5	<0.05	
RCP2A	65663	83W	9821	12.10.83	8.2	94.2	526	290	51	39	79	7	<2	256	146	41	<1	35	0.23	0.4		
RCP3A	65664	83W	9822	8.10.83	8.2	158	892	400	57	62	172	12	<2	385	254	85	5	52	0.49	0.8		
RCP4A	65665	83W	9823	12.10.83	8.3	141	781	340	50	52	153	10	<2	266	253	83	4	43	0.38	0.6		
RCP4P	85934	86X	252	1.11.85	8.1	101	590	262	39	40	108	8	<2	265	159	56	4	46	0.42	0.5		
RCP5A	65666	83W	9824	30.9.83	7.8	326	1830	580	71	98	440	24	<2	250	753	295	1	27	-	1.1		
RCP5B	65667	83W	9825	30.9.83	8.2	353	2040	630	54	120	494	22	<2	348	805	277	12	83	-	1.1		
RCP6A	65668	83W	9826	8.10.83	8.4	161	920	420	56	68	174	12	6	378	263	91	6	55	0.56	0.8		
RCP7A	65669	83W	9827	15.10.83	8.3	71	420	250	50	30	51	5	3	265	80	26	2	40	0.23	0.4		
RCP8A	65670	83W	9828	18.10.83	8.1	147	839	340	50	53	165	10	<2	322	243	98	5	54	0.48	0.7		
RCP9A	65671	83W	9829	10.10.83	8.5	167	904	330	41	55	207	13	15	271	352	36	2	47	0.72	1.1		
RCP10A	65672	83W	9830	25.10.83	8.3	112	651	300	50	43	113	8	6	293	177	58	3	46	0.39	0.6		
RCP10P	85935	86X	253	6.11.85	8.3	98	590	266	44	38	103	8	3	296	135	57	3	46	0.39	0.6		
RCP11A	65673	83W	9831	21.10.83	8.2	118	673	270	49	35	138	8	<2	284	213	47	1	40	0.49	0.4		
RCP12A	65674	83W	9832	18.10.83	8.2	113	656	300	51	42	114	8	<2	293	184	62	2	46	0.38	0.5		
RCP13A	65675	83W	9833	20.10.83	8.2	110	650	280	48	40	118	8	<2	291	179	61	3	47	0.40	0.6		
RCP14A	65676	83W	9834	19.10.83	8.3	105	602	310	57	41	94	7	6	256	167	53	2	47	0.31	0.4		
RCP15A	65677	83W	9835	19.10.83	8.4	107	627	310	57	42	100	7	15	287	151	58	3	50	0.41	0.5		
RCP16A	65687	84X	2039	30.8.84	8.2	125	740	355	50	56	125	10	<2	326	215	70	3	46	0.4	0.6		
RCP17A	65688	84X	2040	23.8.84	8.3	176	1030	427	36	82	199	17	3	400	321	104	6	58	-	1.1		
RCP18A	65689	84X	2041	21.8.84	8.2	201	1180	476	39	92	236	18	<2	404	392	125	8	64	-	1.2		
RCP19A	65690	84X	2042	20.8.84	8.2	473	2810	807	63	158	721	40	<2	445	1180	347	11	69	-	1.6		
RCP20A	65691	84X	2043	24.8.84	8.2	114	680	303	49	44	123	9	<2	300	185	71	<1	46	0.44	0.6		
RCP21A	65692	84X	2044	28.8.84	8.2	82.6	490	236	45	30	77	6	<2	241	123	41	1	49	0.31	0.5		
RCP22A	65693	84X	2045	15.6.84	8.1	132	780	364	62	51	132	9	<2	349	222	73	2	52	0.43	0.7		
SEC BF2-1			22.10.81	8.0	92	-	-	-	61	34	77	6	<1	285	136	52	2	-	-	0.3	<0.05	
SEC BF2-1	85936	86X	254	11.11.85	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.13	
SEC BF2-2			30.10.81	8.1	91	-	-	-	62	34	75	6	<1	276	136	52	2	-	-	0.3	<0.05	
SEC BF2-2	85937	86X	255	14.11.85	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.08	

TREALLA LIMESTONE

The Trealla Limestone is mostly clay and generally forms an impermeable base to the Robe River alluvium. However, at RCP 4 it is composed of fissured limestone which is in hydraulic continuity with the alluvial gravel (Figure 5, section EE').

An 8-hour pumping test carried out at RCP 4 at a rate of 980 m³/d indicated a hydraulic conductivity of 220 m/d, similar to the gravel of the Robe River alluvium.

In spite of the marked difference in lithology, the salinity and chemical composition of the groundwater at RCP 4 is similar to that in the Robe River alluvium (Figure 15)

YARRALLOOLA CONGLOMERATE

The Yarraloola Conglomerate was encountered at RCP 4 and RCP 5A where it underlies Trealla Limestone and alluvium respectively. To the northwest it underlies impermeable Cretaceous and Tertiary sediments and grades laterally into the Birdrong Sandstone which is an extensive aquifer throughout the Carnarvon Basin (Allen, 1987). The base of the formation is exposed in outcrops south and east of the investigation area, and these isolated outcrops are therefore unsaturated.

The Yarraloola Conglomerate has a low permeability where intersected below the Robe alluvial aquifer. For example, RCP 5A was drilled in a zone of low seismic velocity (Nowak, 1979), usually indicative of relatively high porosity, but the bore yield was very low.

The Birdrong Sandstone aquifer beneath the coastal plain is presumably recharged through the Robe River

alluvium where the Robe River enters the coastal plain. Pressure data from oil wells in the formation indicate a potentiometric head of about 40 m above sea level throughout the area (Thomas, 1978). This is consistent with a very low rate of recharge originating in the subcrop beneath the Robe River alluvium where the water table is 40-43 m above sea level. Artesian flows from the formation have been encountered in the northern part of the investigation area and along the coast (Thomas, 1978).

The groundwater salinity in the Yarraloola Conglomerate rises from 2000 mg/L at RCP 5A to about 5000 mg/L in oil exploration bores near RCP 13 and to 20 000 mg/L at the coast (Thomas, 1978).

The low permeability, very low potentiometric gradient, relatively high salinity, and small area of potential recharge indicates that recharge (and therefore leakage from the Robe River alluvium) is likely to be very small.

DEVELOPMENT

The area of the Robe River alluvium, including a small area of Trealla Limestone, most suitable for groundwater abstraction is a 2 km-wide strip extending about 7 km along the river from RCP 4 and the SEC bores northwestwards to RCP 10. Within this area the aggregate saturated thickness is at least 5 m and the salinity range is 450-700 mg/L.

Bore yields of 1000-1300 m³/d have been demonstrated by pumping tests, and the potential yield of one bore (SEC 2/2), which was not pumped to the limit of the available drawdown, is projected to be 3000 m³/d.

The yield of the aquifer is limited ultimately by the recharge from flows in the Robe River, which depends on the duration of river flow and the storage level in the aquifer. The mean annual runoff (1972-85) is $51 \times 10^6 \text{ m}^3$, but in the driest five year period (1975-9) the average annual streamflow was only $11 \times 10^6 \text{ m}^3$; however since these flows do not reach the sea, a high proportion must contribute to groundwater recharge.

The estimated recharge, based on the decline in storage in a year of no river flow, and the limitation of river flow suggest that $10 \times 10^6 \text{ m}^3$ would be a reasonable upper limit for annual abstraction. The estimated groundwater in storage of $70 \times 10^6 \text{ m}^3$ could be utilized in periods of below average runoff.

The infiltration capacity of the aquifer could be increased by lowering the water table close to the river and creating a larger immediately available storage capacity to be filled when the river flowed. By artificially slowing river flow, and by increasing the area available for direct infiltration, the storage capacity of the normally unsaturated gravel above the water table away from the river could also be utilised.

The salinity of the groundwater could also be modified as increased infiltration may capture a higher proportion of the low salinity water occurring at flow peaks.

CONCLUSIONS

Alluvial gravels underlying and adjacent to the Robe River are a significant source of unutilized fresh groundwater in a region generally deficient in fresh groundwater resources. The resources are sufficiently large to maintain a town water supply or irrigated agriculture.

The aquifer has the potential to yield about $10 \times 10^6 \text{ m}^3$ per year of groundwater, with individual bore yields of up to $3000 \text{ m}^3/\text{d}$. A borefield situated close to the river could create storage in the aquifer and when runoff occurred allow increased recharge and utilization of surface water which would normally flow to the sea. This would also lead to a lowering of the groundwater salinity.

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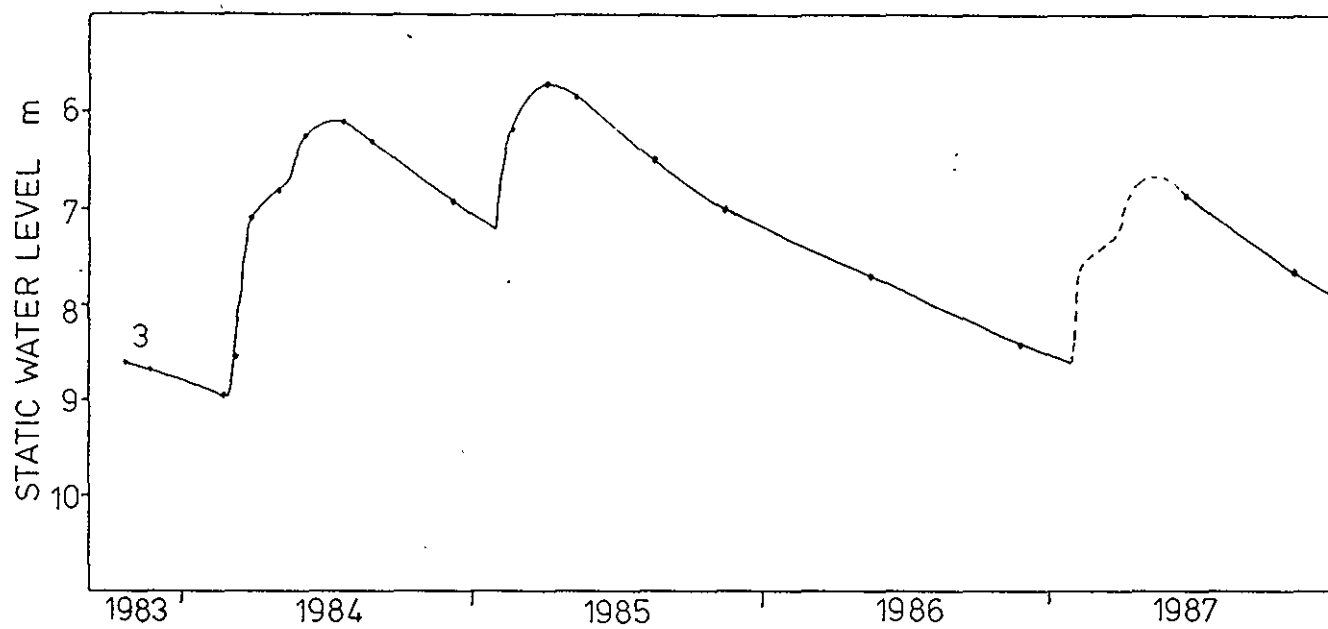
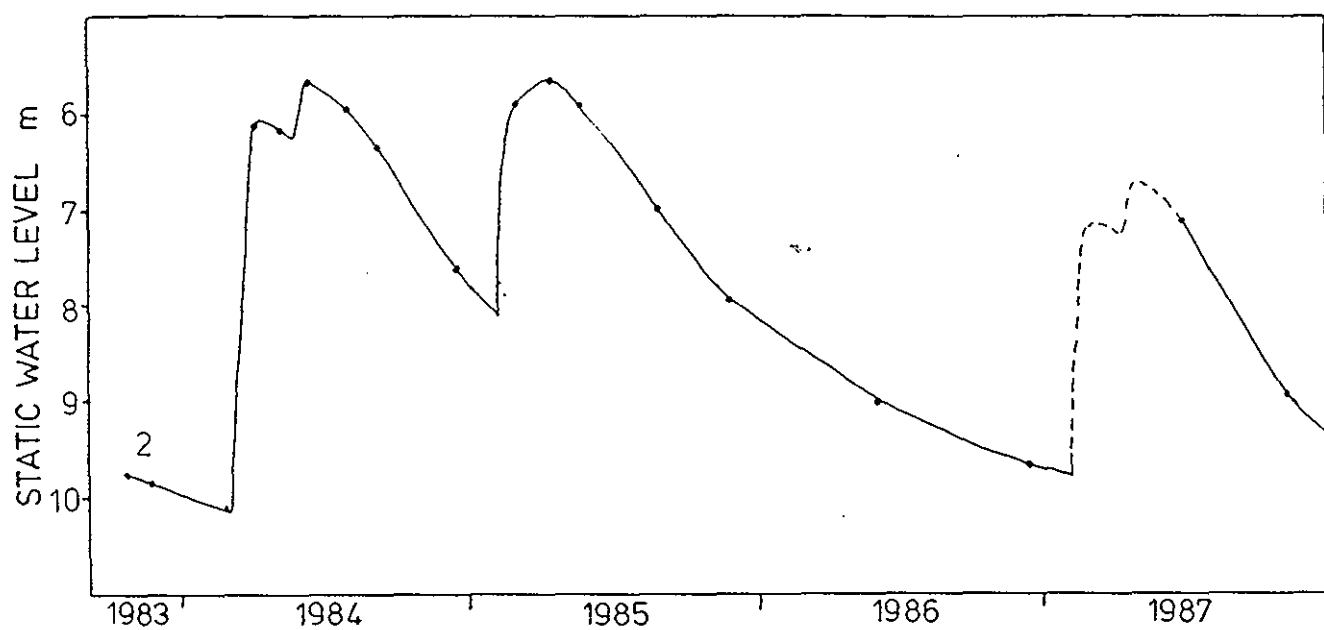
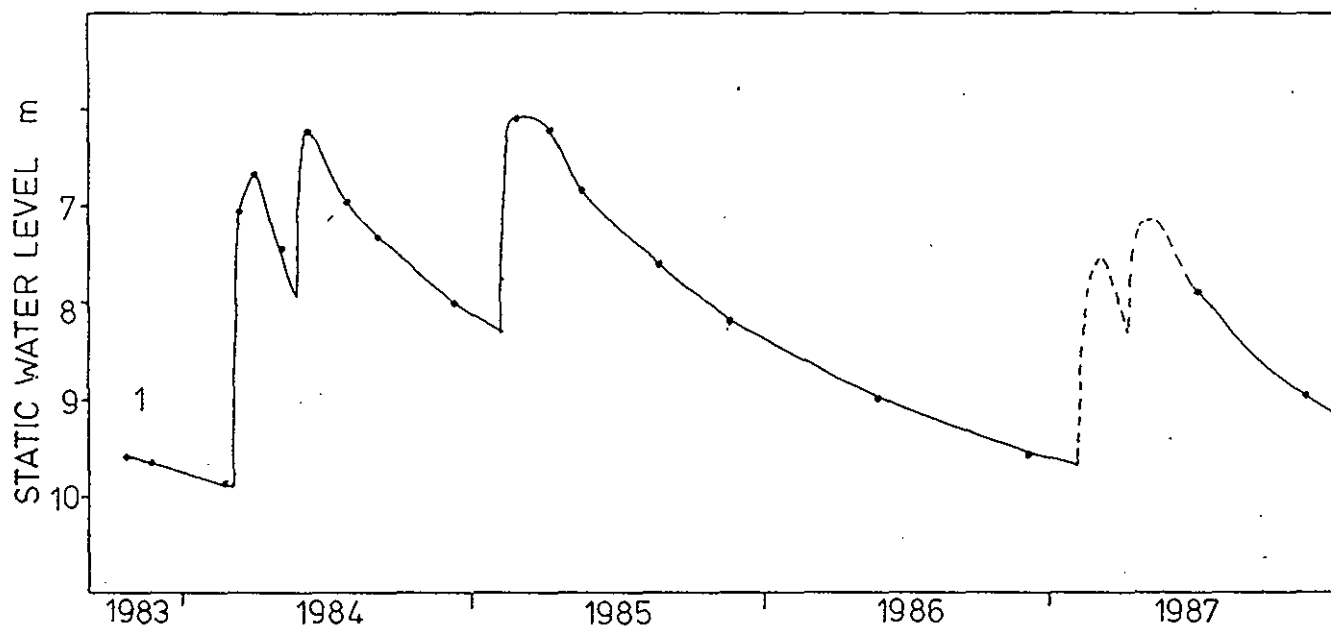
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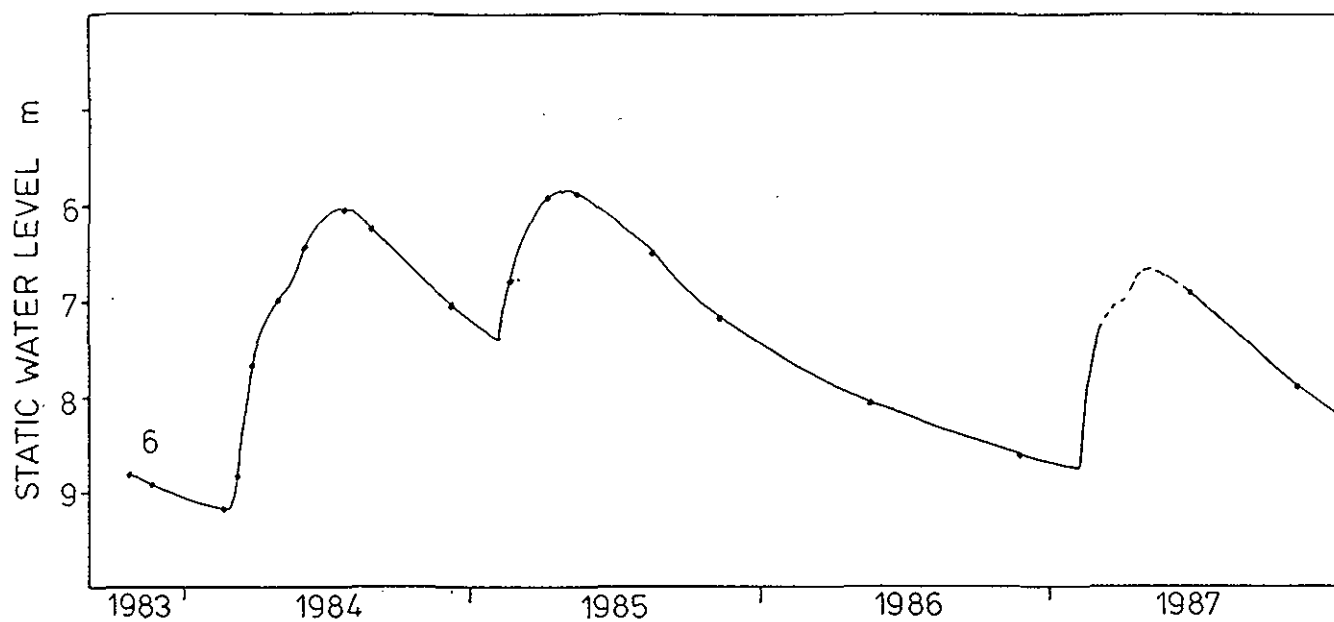
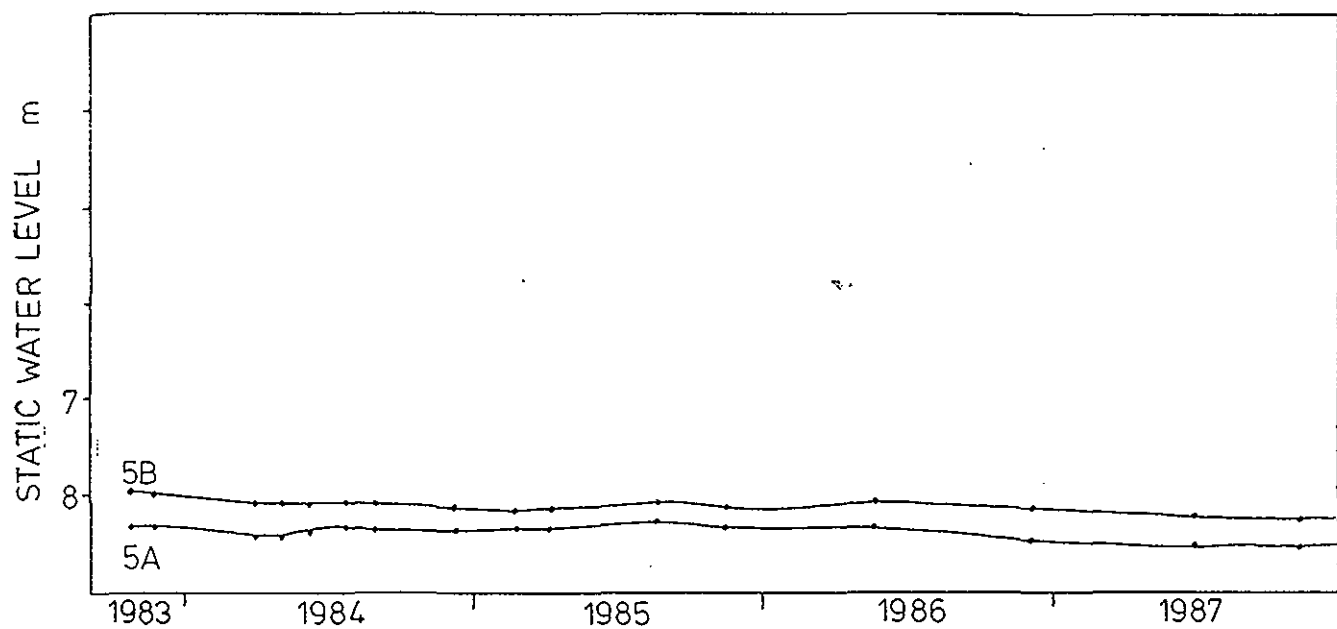
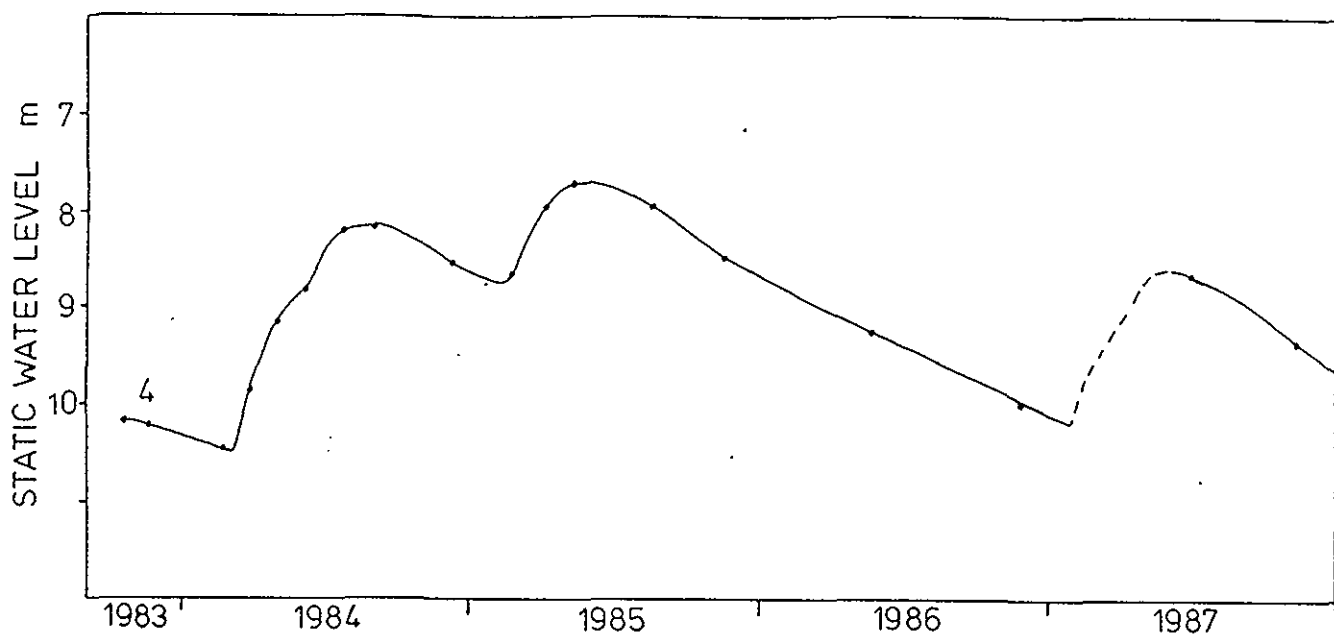
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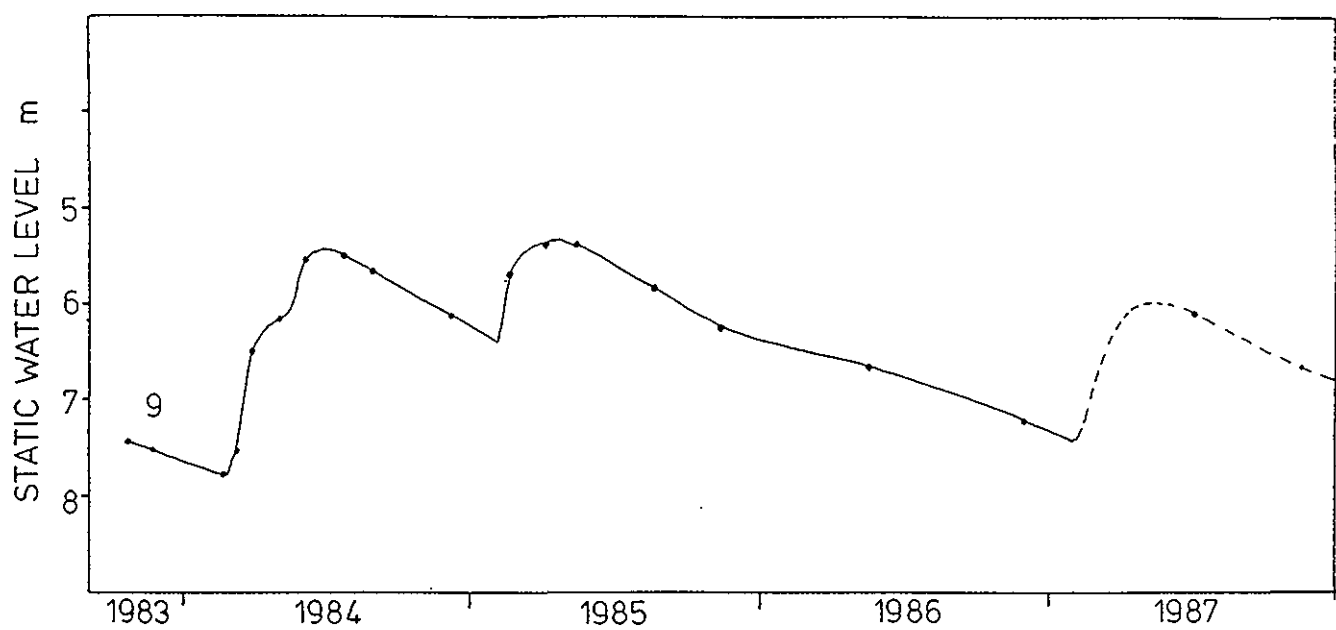
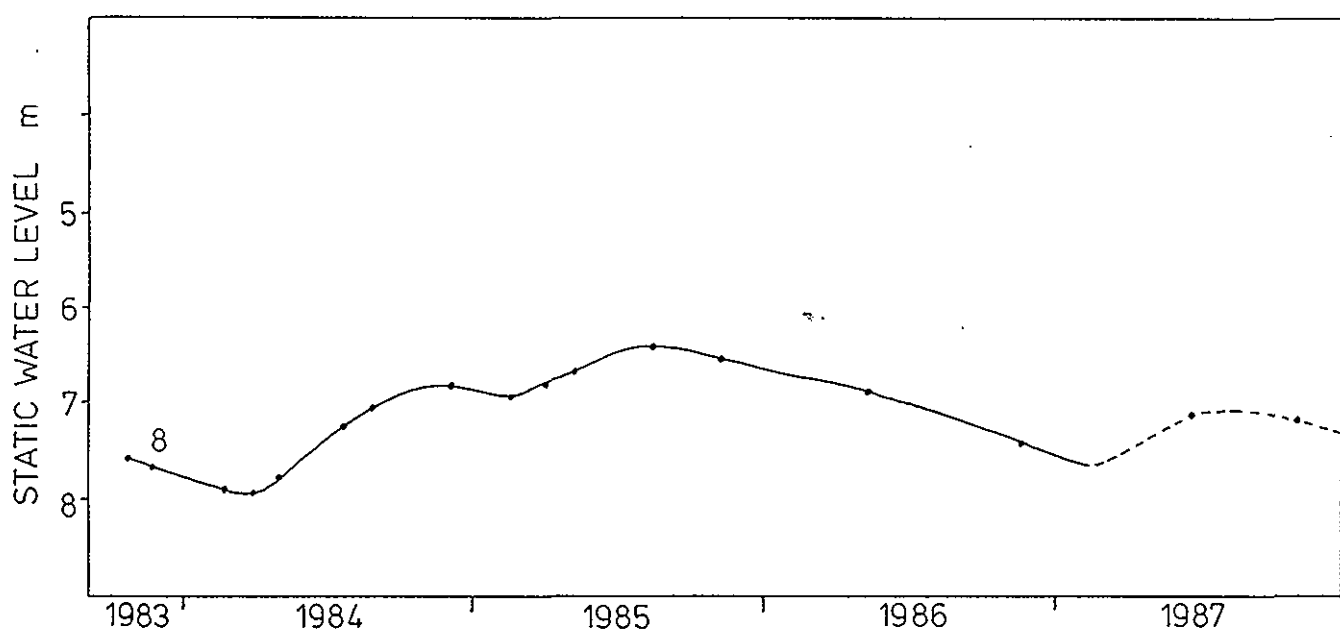
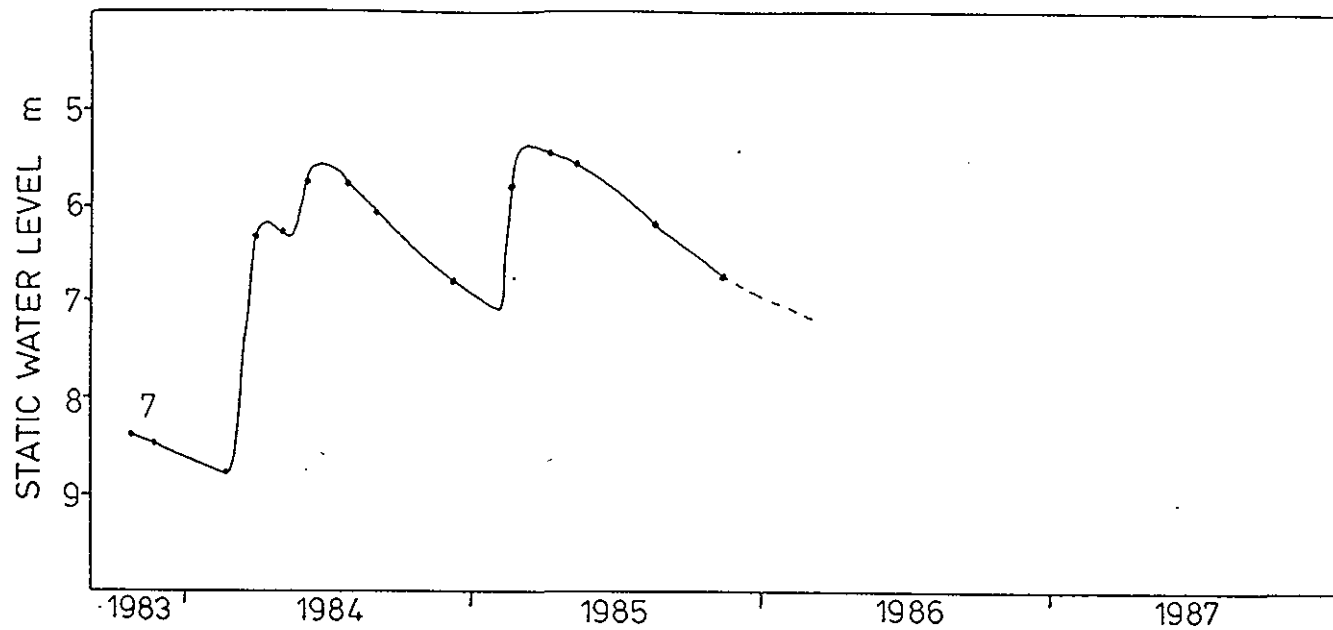
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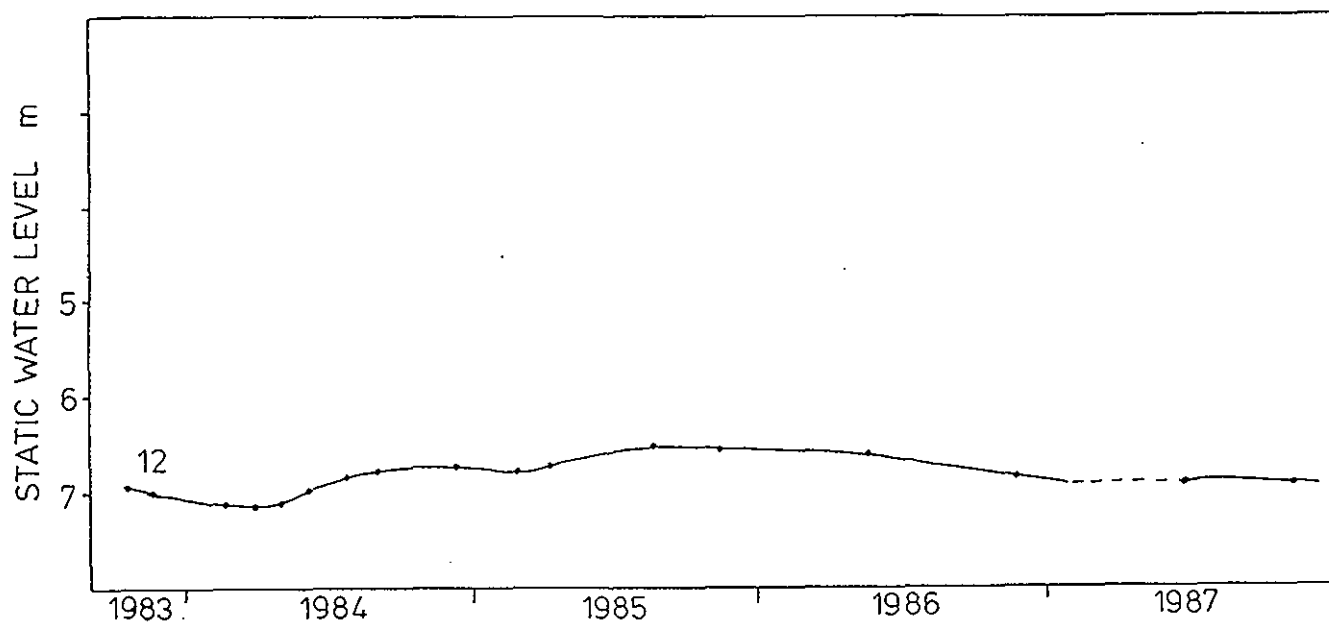
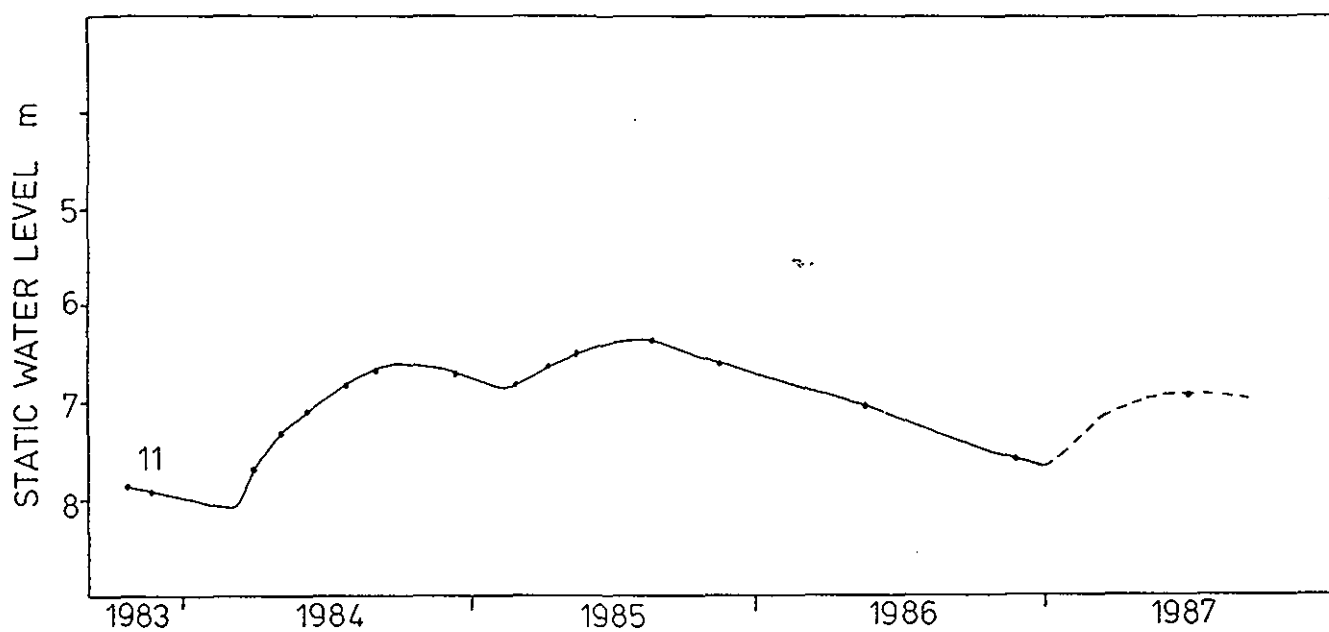
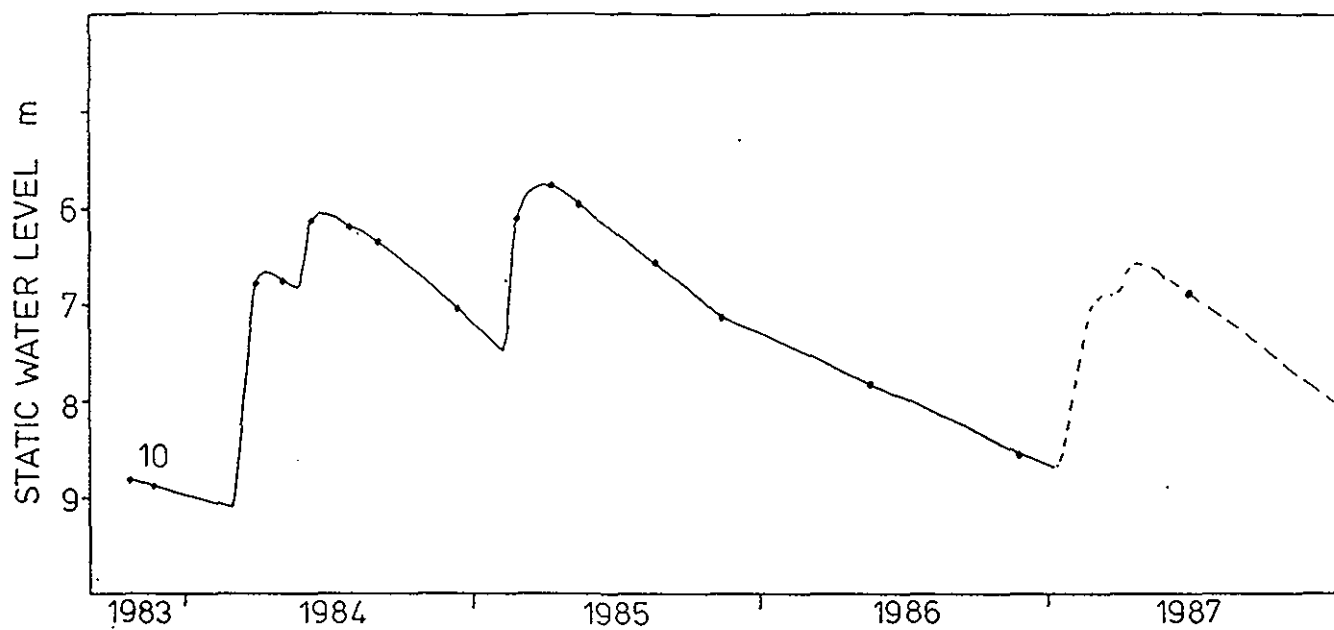
APPENDIX

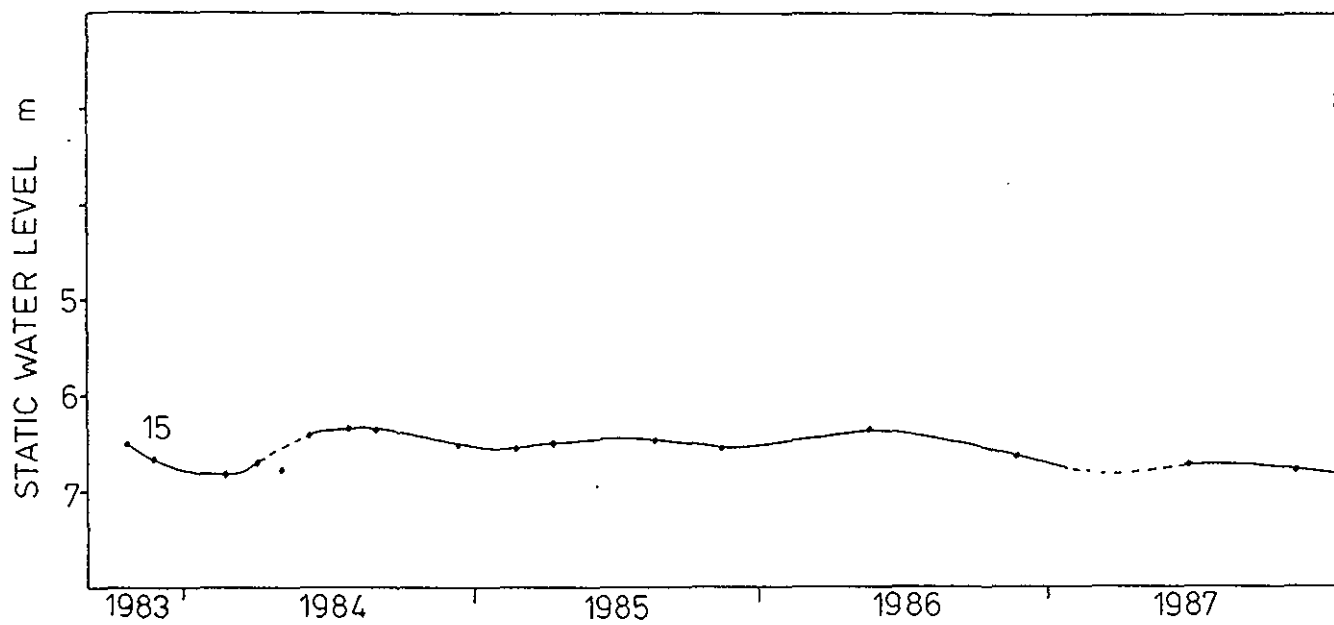
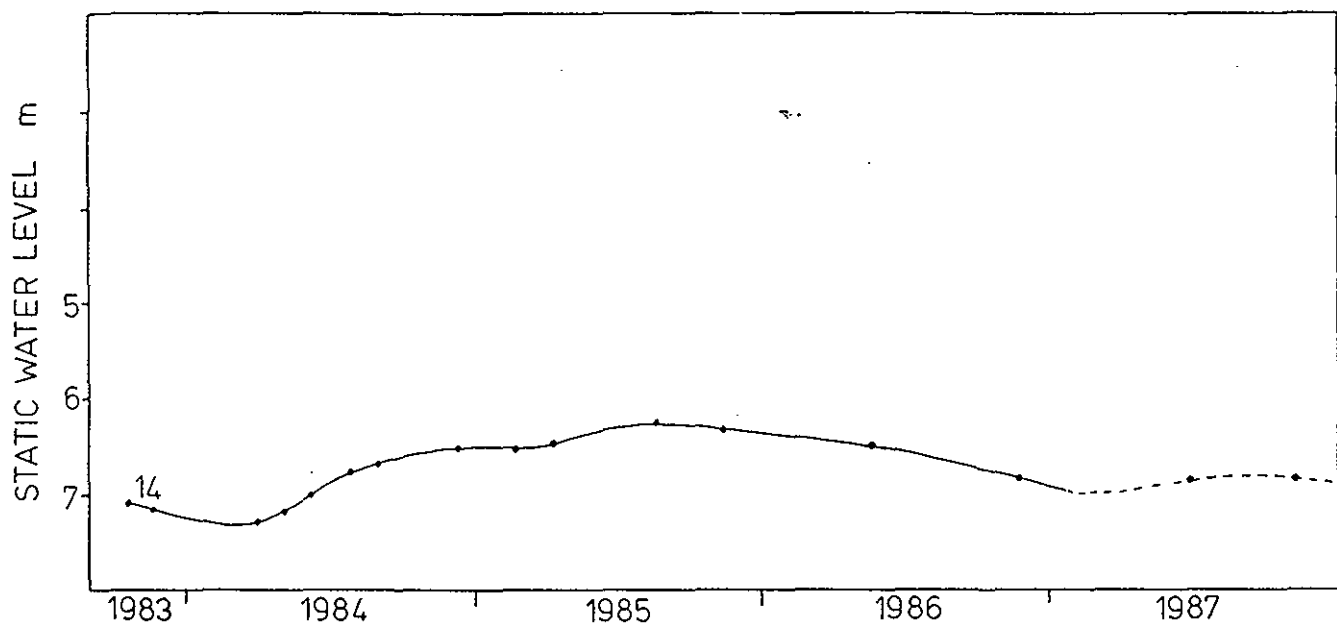
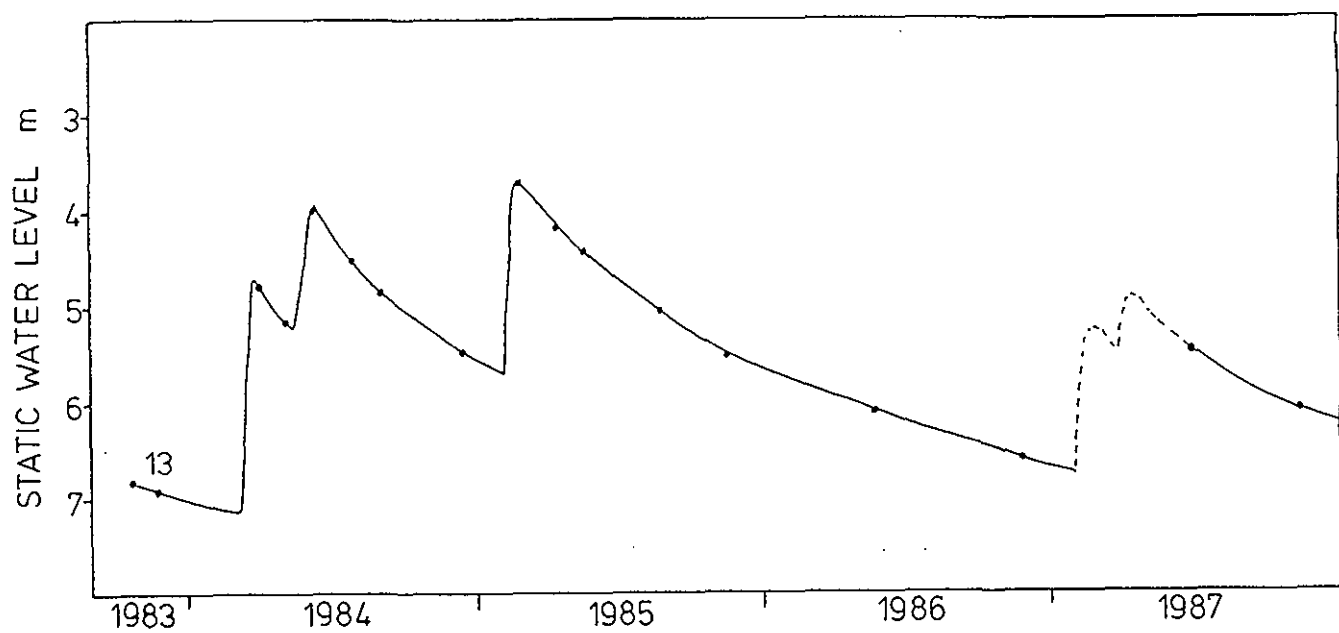
HYDROGRAPHS-
ROBE COASTAL PLAIN BORES 1-22

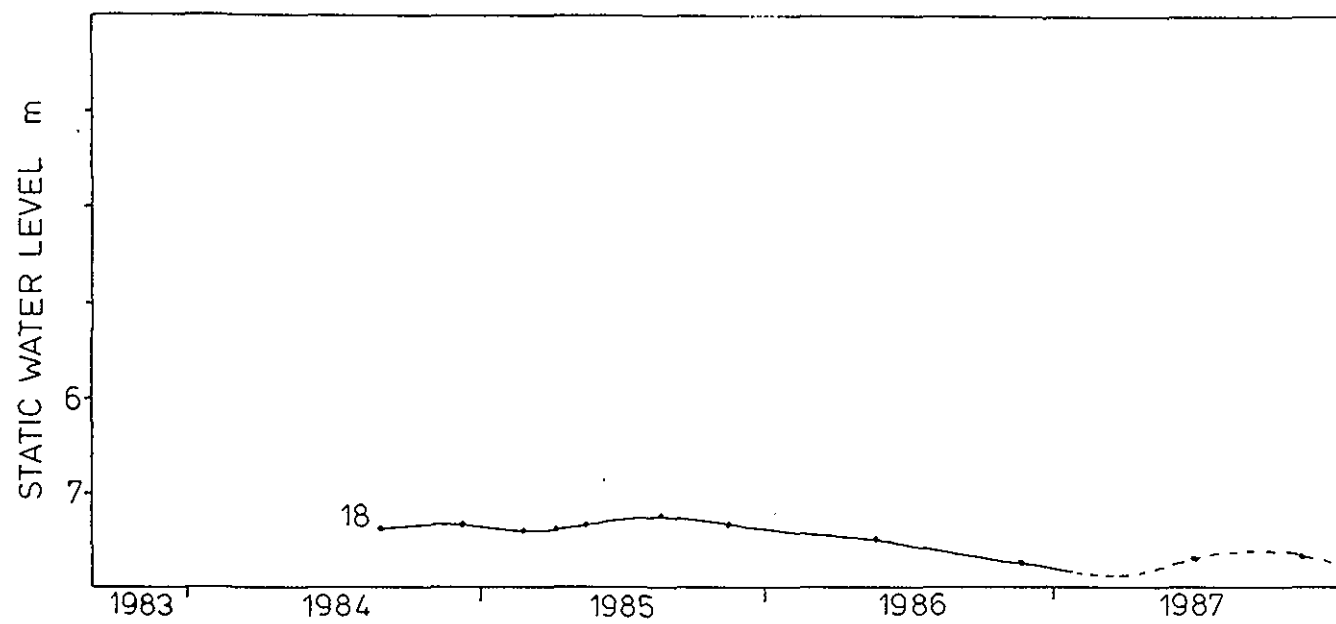
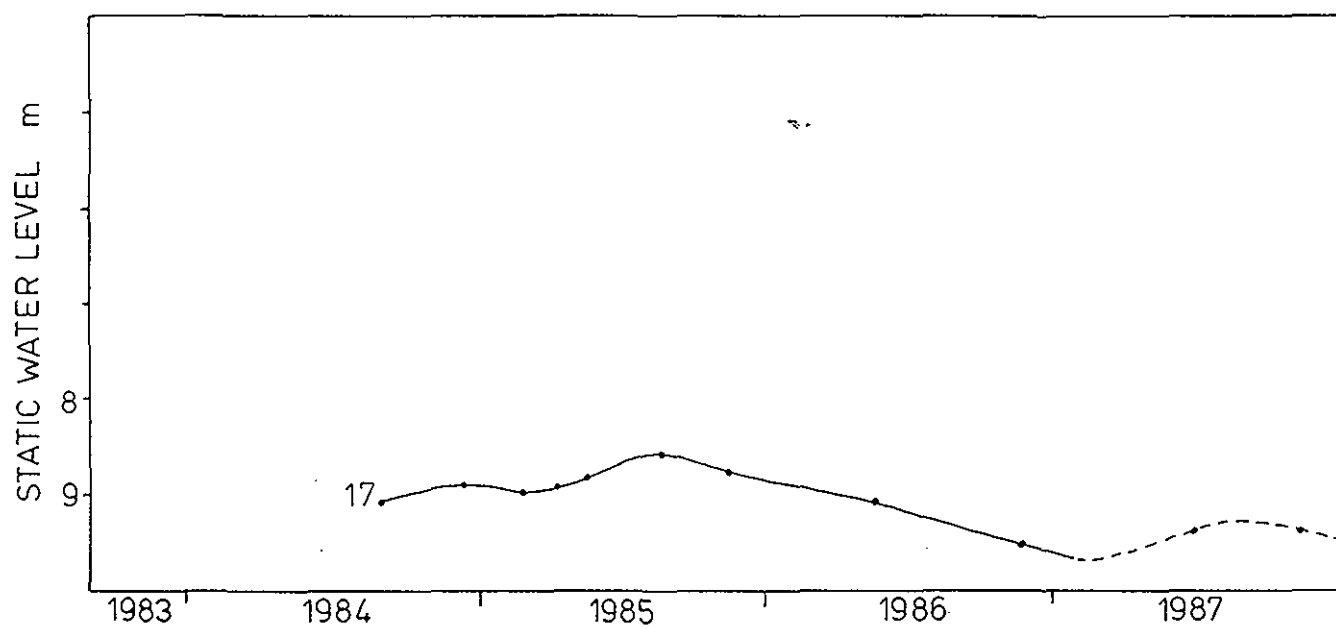
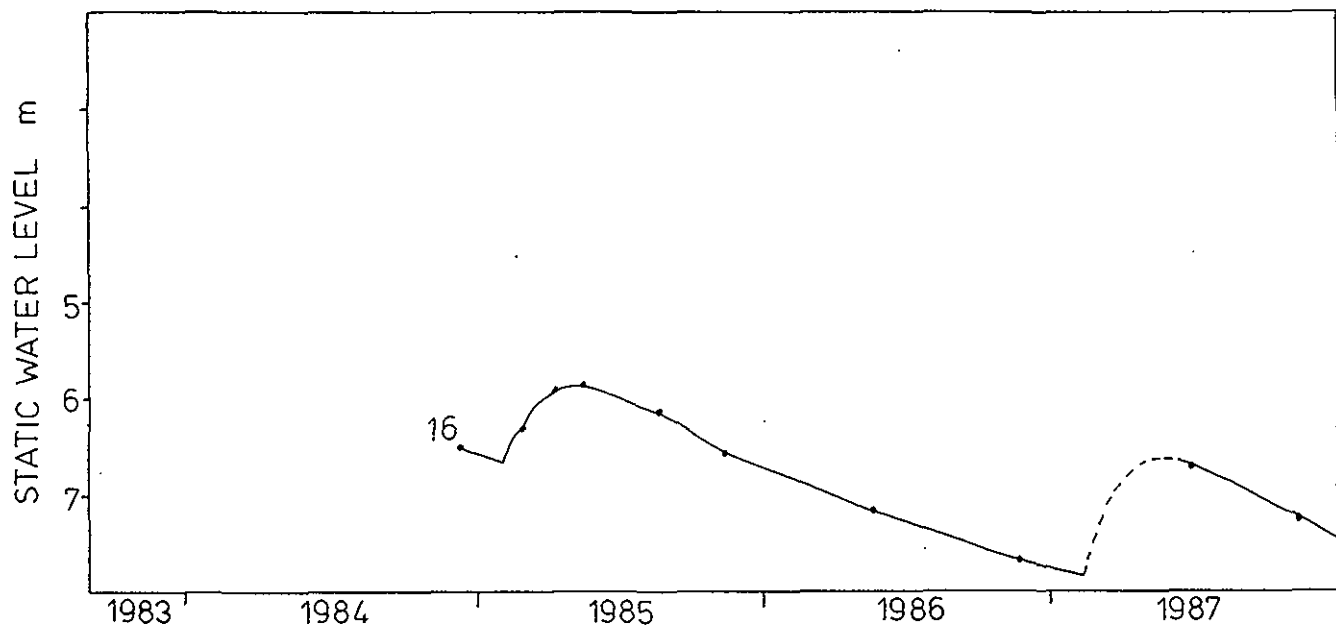


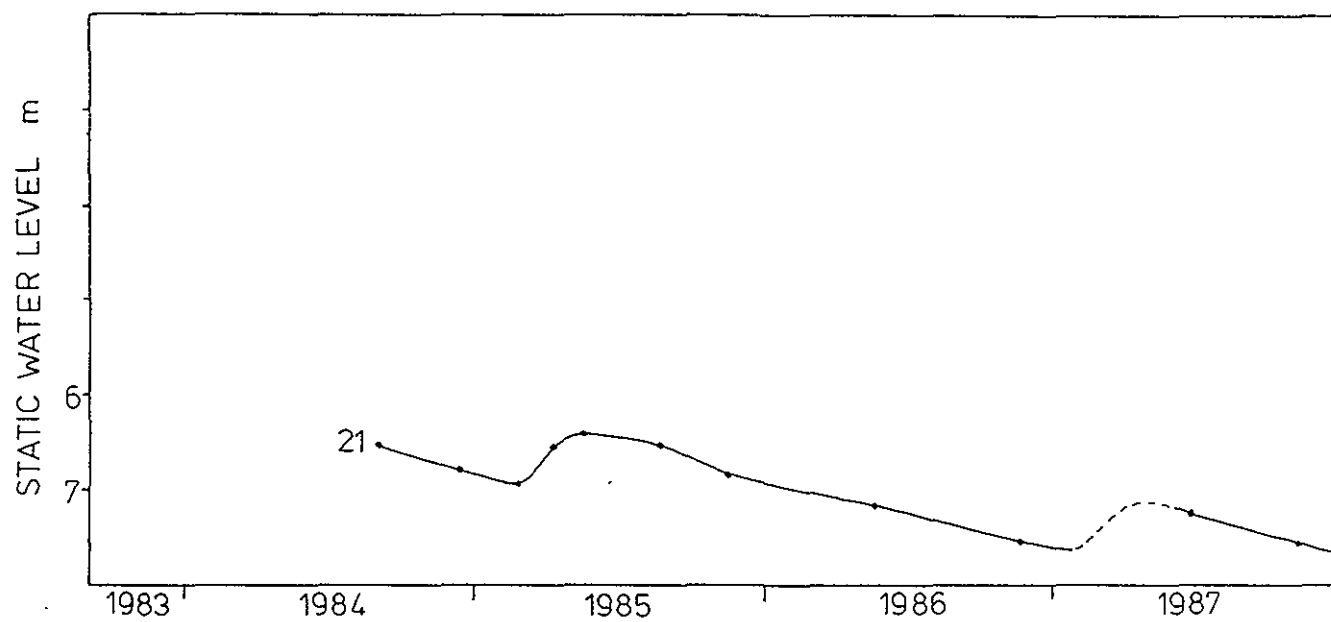
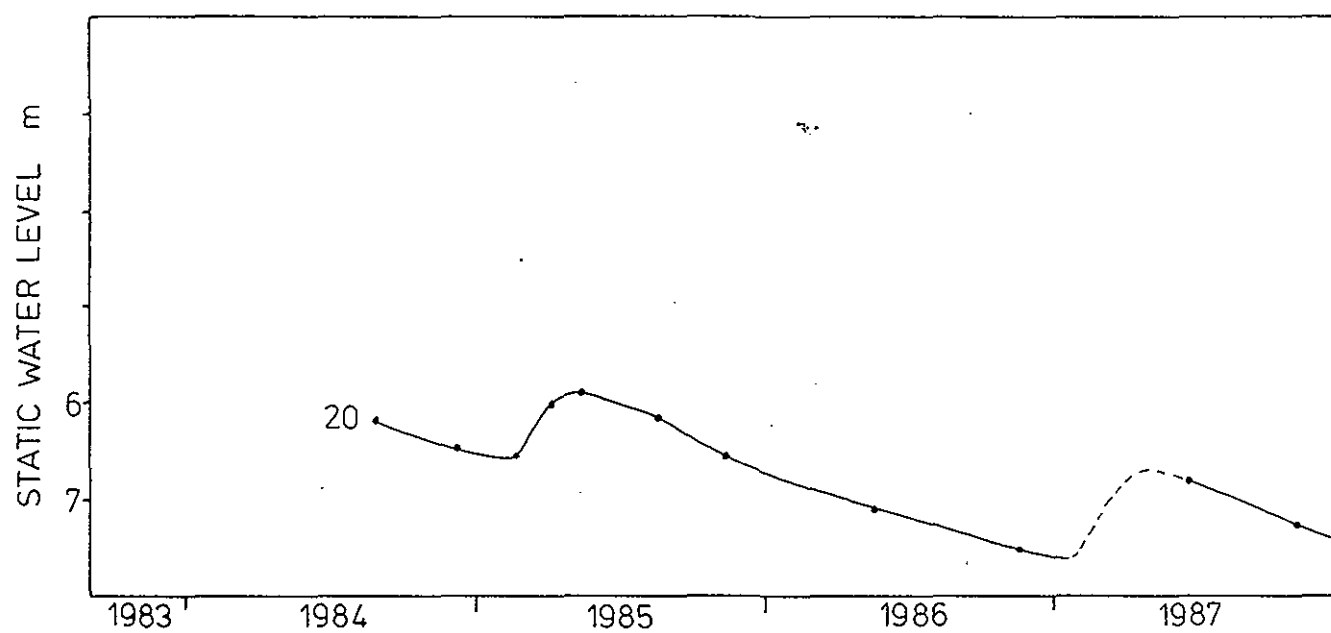
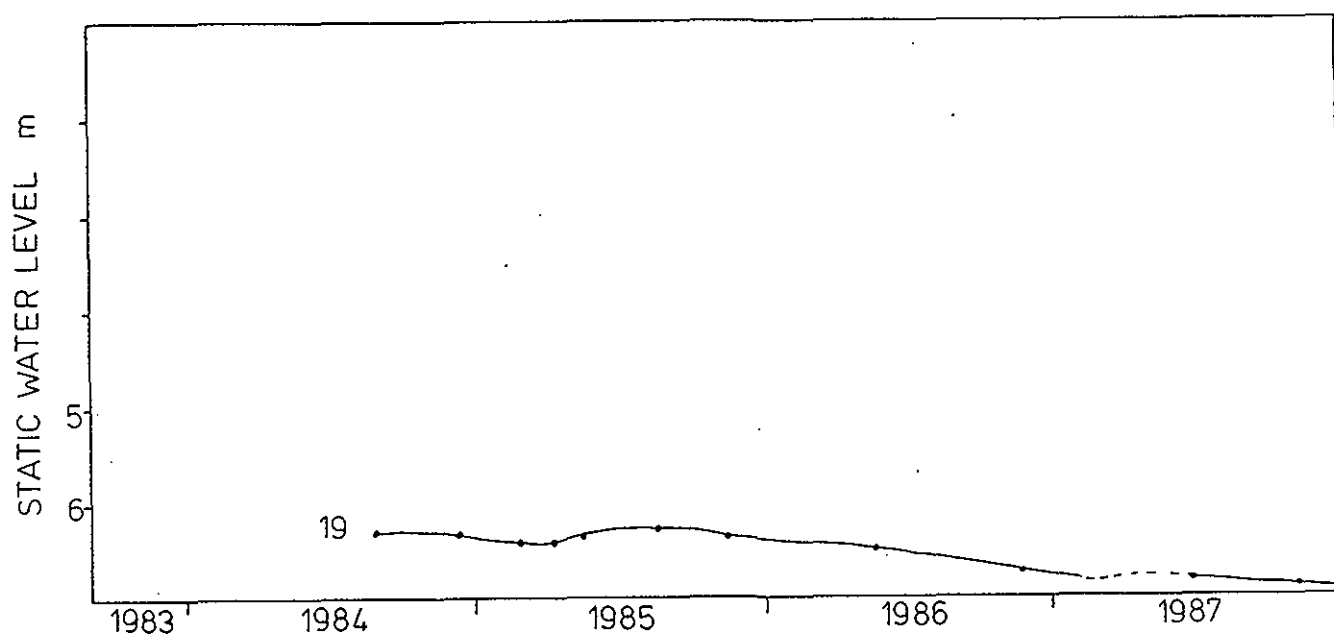


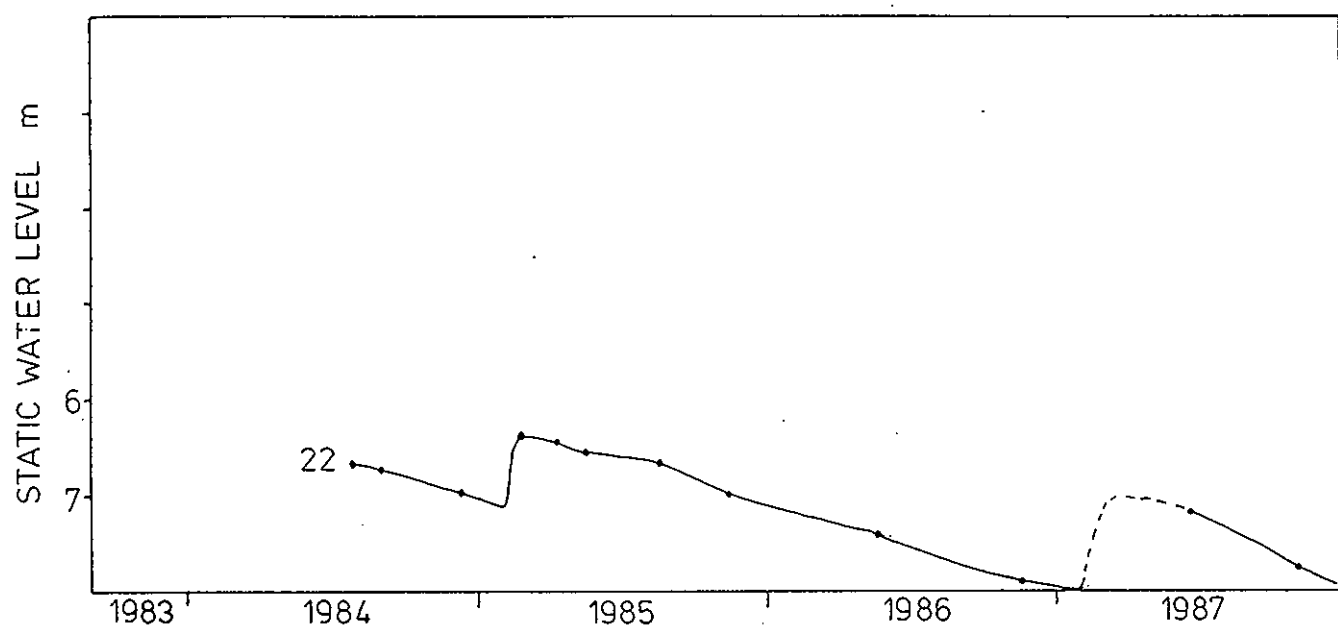


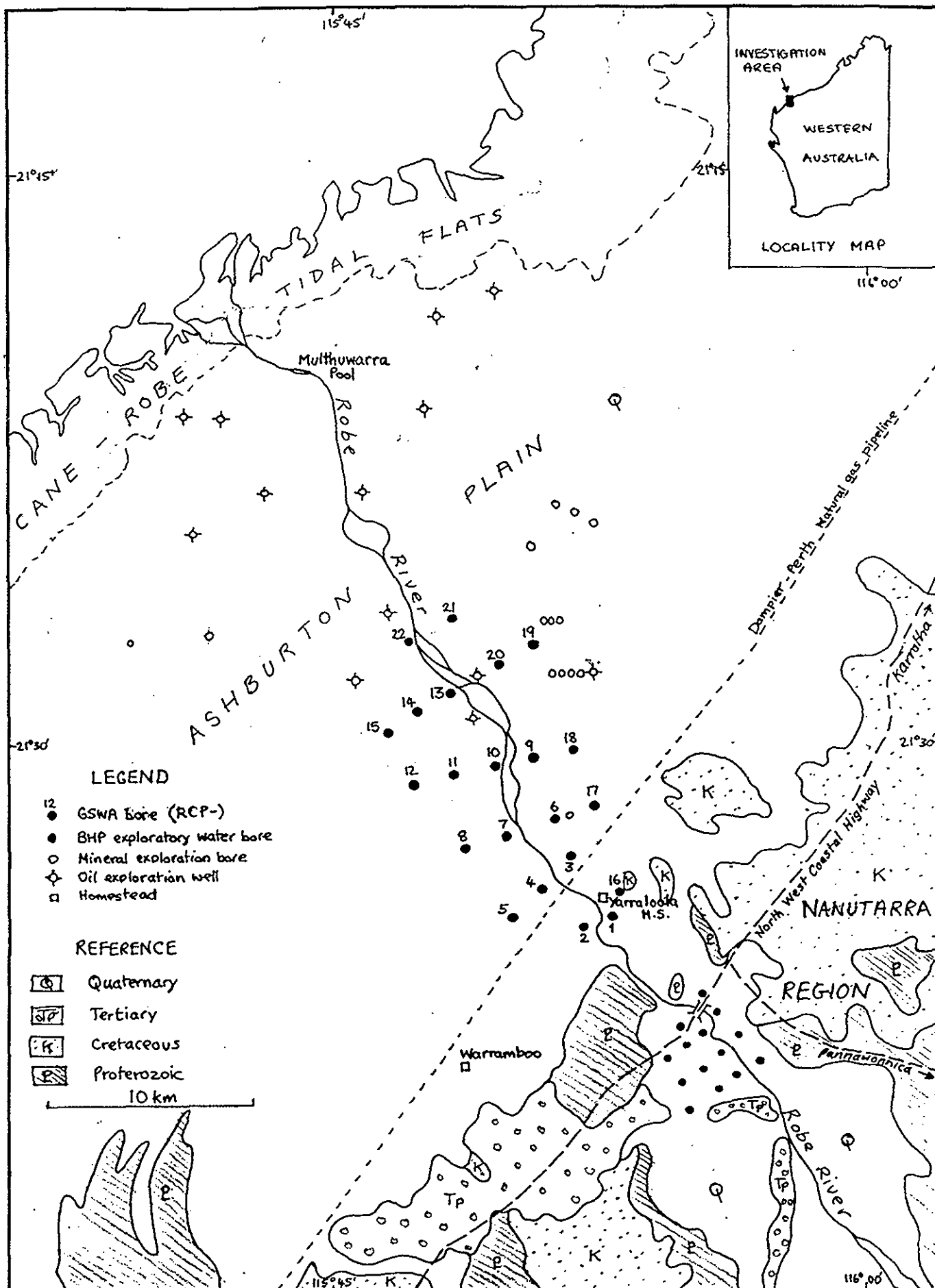












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DRAWN		
CHKD		
APVD		

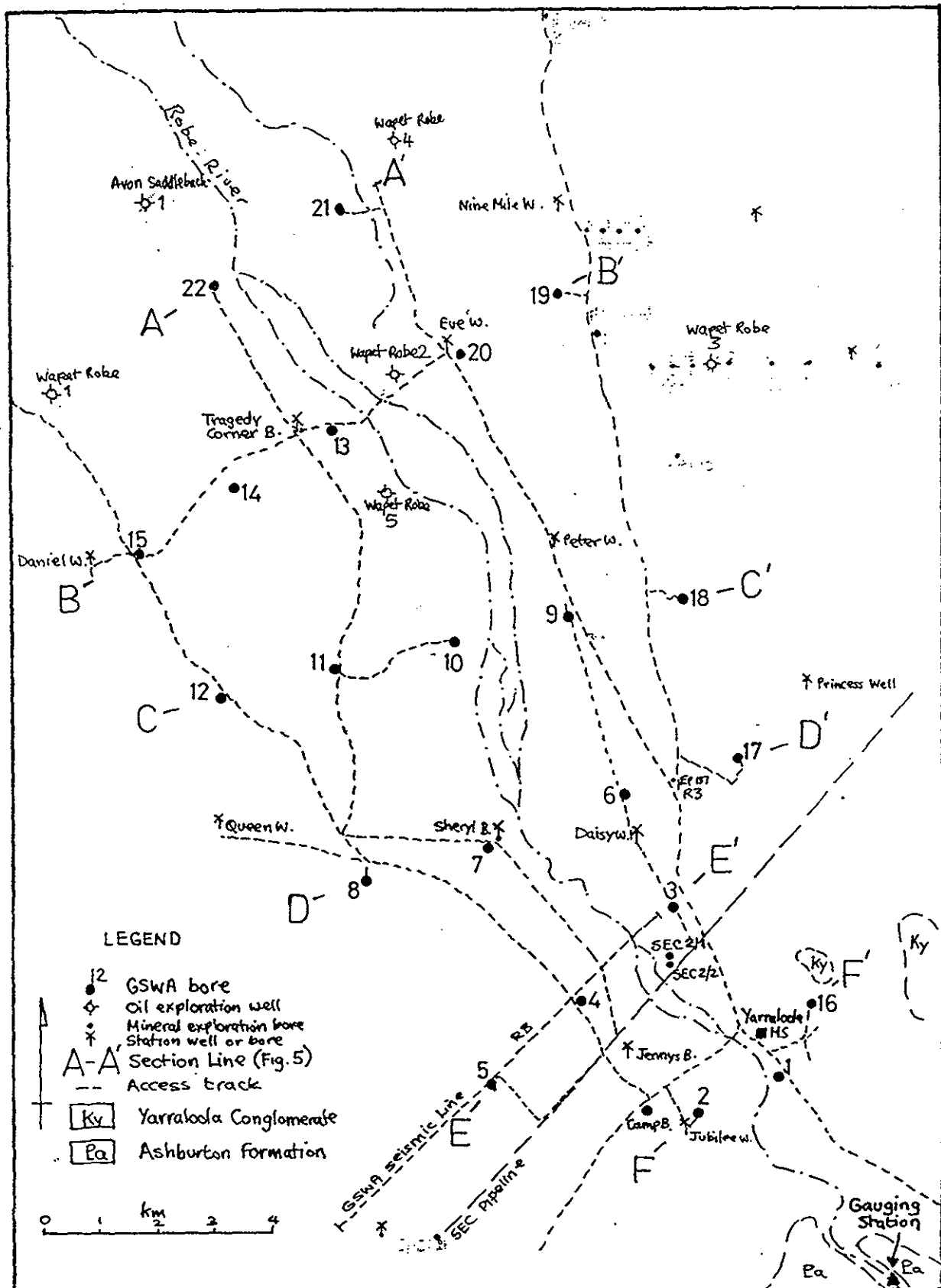
FIG. 1: LOCATION AND GEOLOGY

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SF 50-6



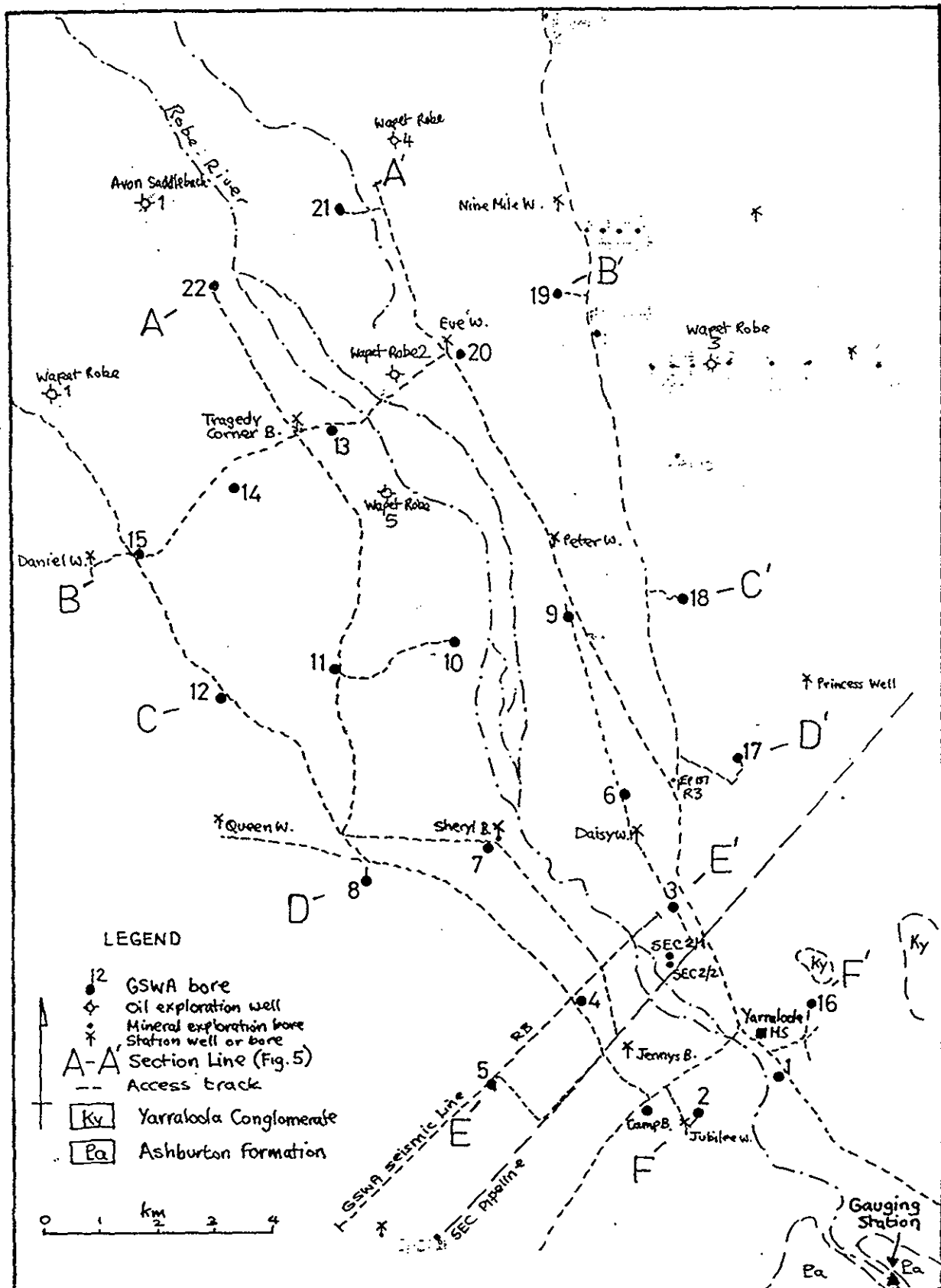
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Apvd		

FIG. 2: BORE LOCATIONS

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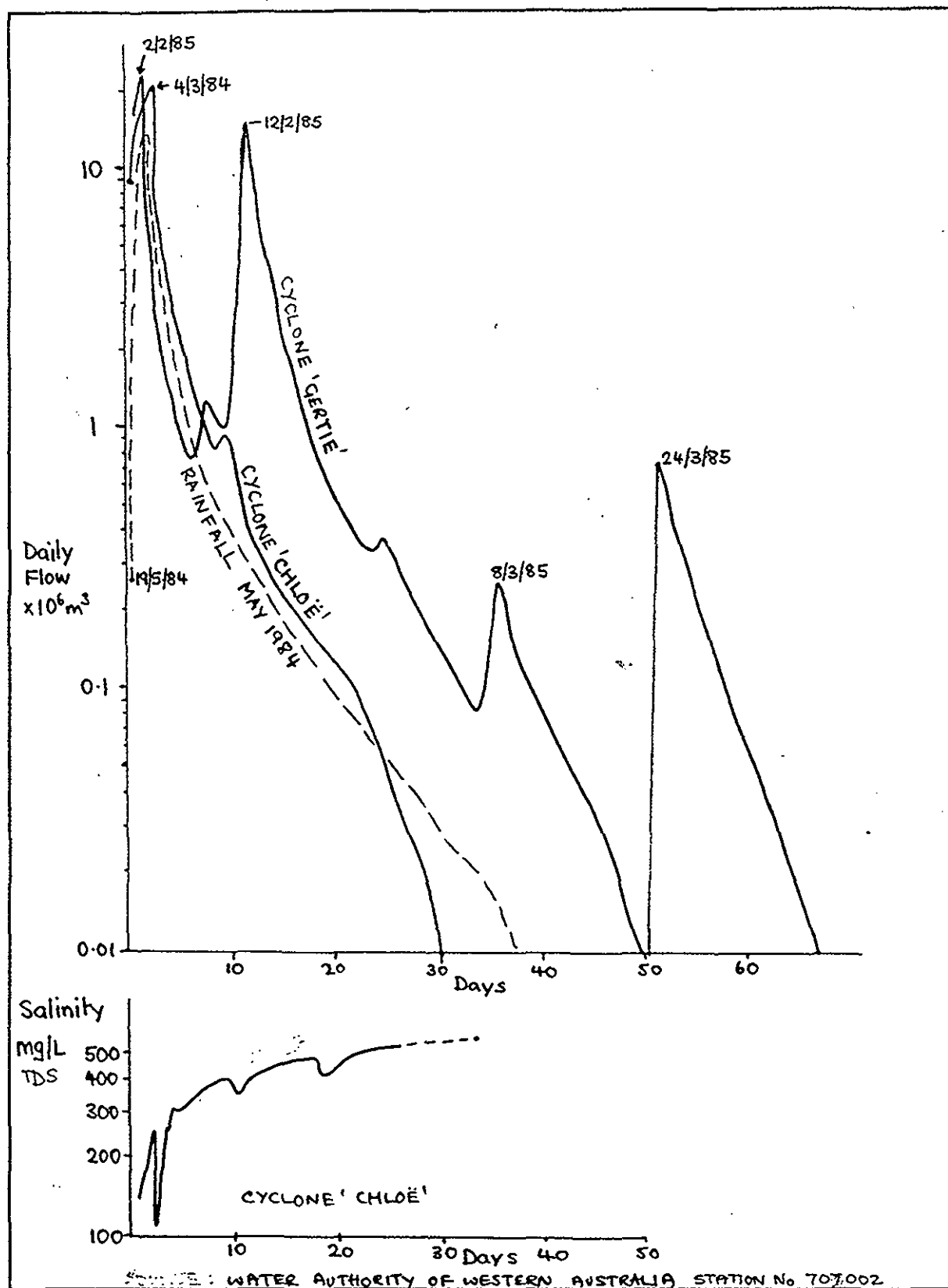
FIG. 2: BORE LOCATIONS

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SF 50-6

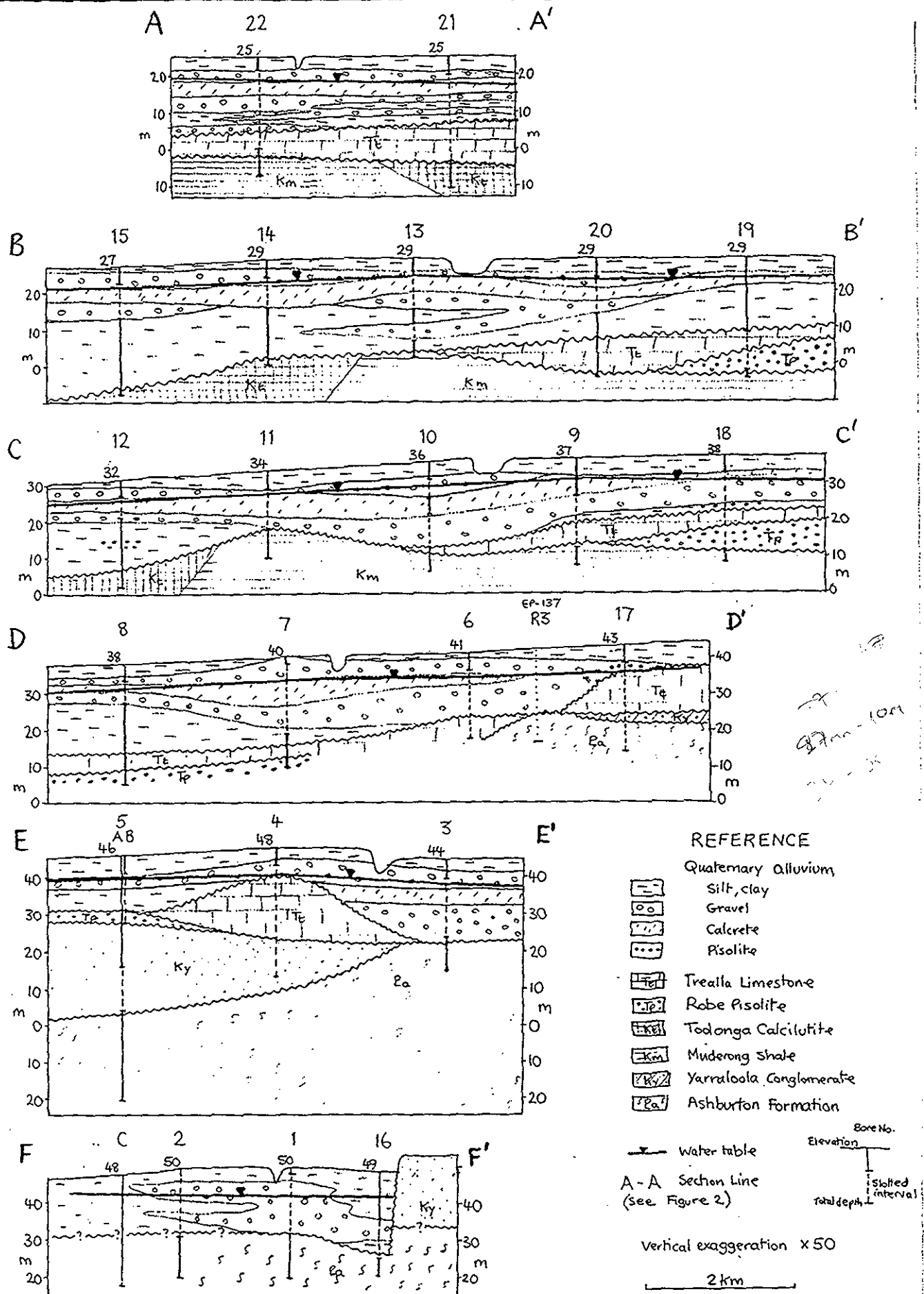
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GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

	Initial	Date	FIG. 4: ROBE RIVER - FLOW RATE (1984-5) AND SALINITY (1984)	Map Index <table border="1"><tr><td></td><td></td><td></td><td></td><td></td></tr><tr><td></td><td></td><td></td><td></td><td></td></tr><tr><td></td><td></td><td></td><td></td><td></td></tr><tr><td></td><td></td><td></td><td></td><td></td></tr><tr><td></td><td></td><td></td><td></td><td></td></tr></table>																									
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Long
Thurs day
get
\$30
250m Thursday New



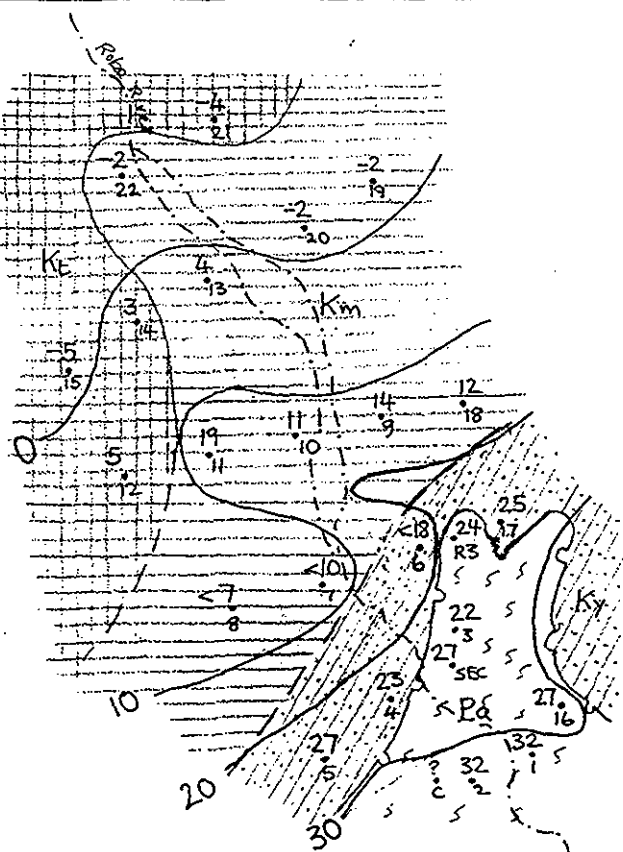
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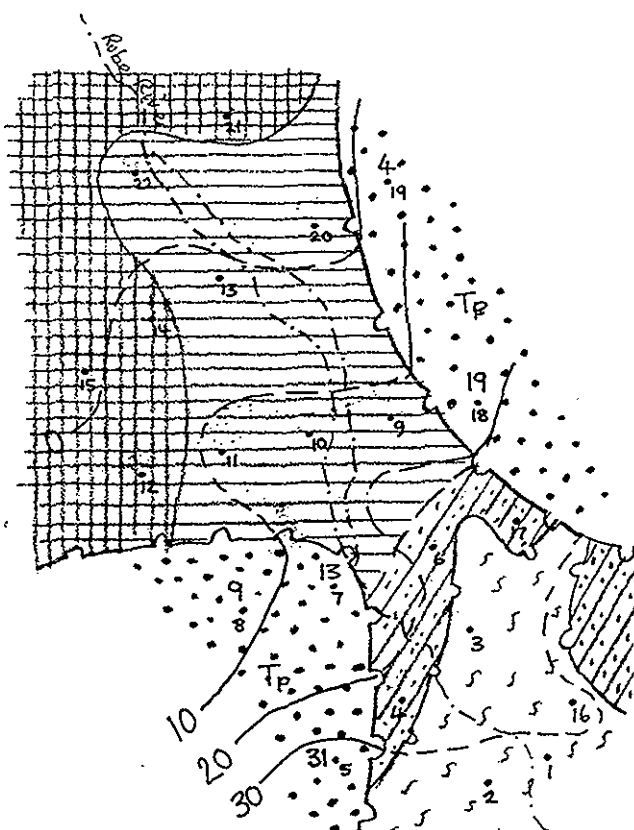
FIG. 5: GEOLOGICAL SECTIONS

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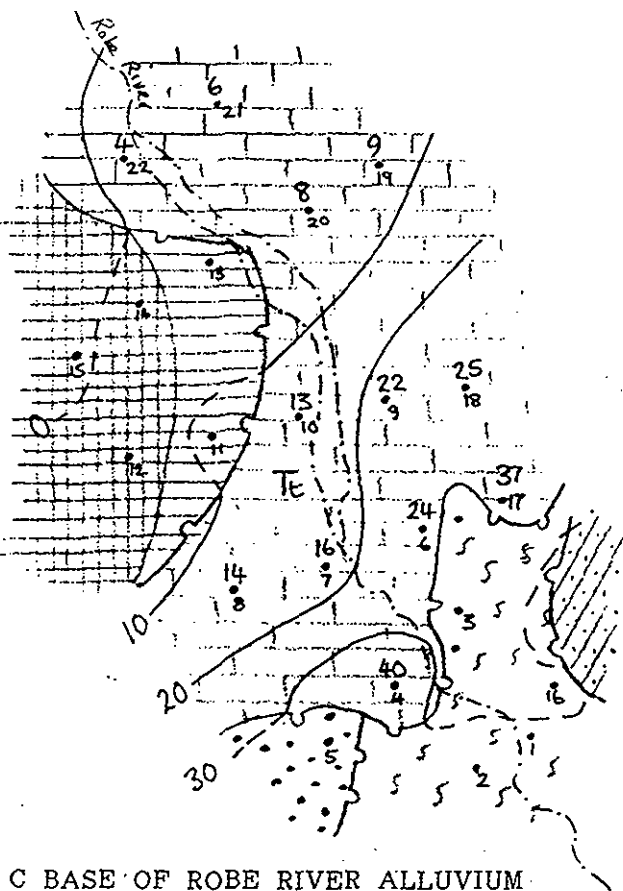
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A BASE OF TERTIARY AND QUATERNARY



B BASE OF TREALLA LIMESTONE AND ROBE RIVER ALLUVIUM



C BASE OF ROBE RIVER ALLUVIUM

REFERENCE

- Trealla Limestone
- Robe Pisolite
- Toolonga Calcilutite
- Muderong Shale/Windalia Radiolarite
- Yarraloola Conglomerate
- Ashburton Formation

25 Elevation of upper surface of mapped formation (m AHD)

-20- Structure contour

Unconformity

5 km

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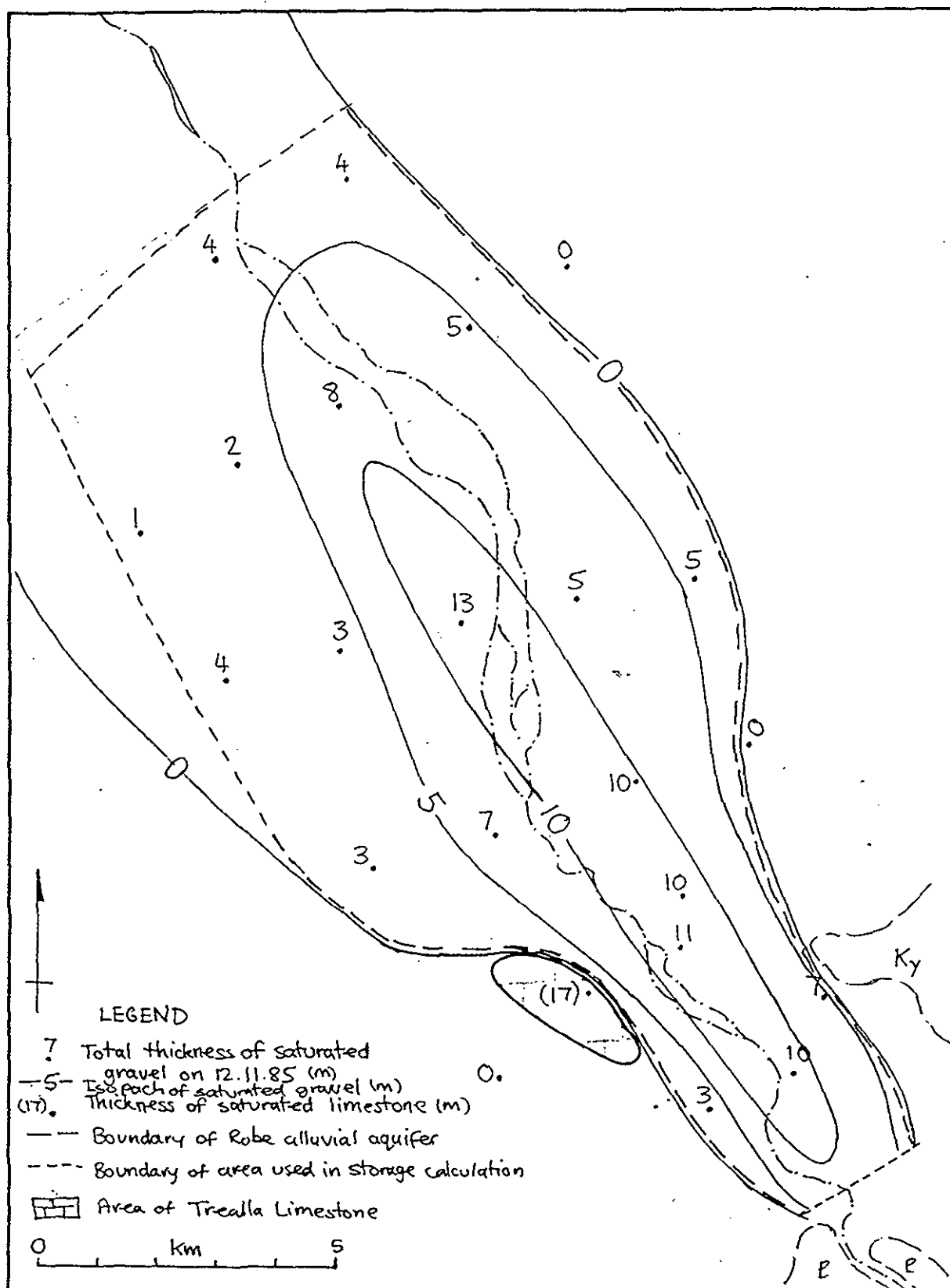
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FIG. 6: SUBCROP AND STRUCTURE CONTOUR MAPS


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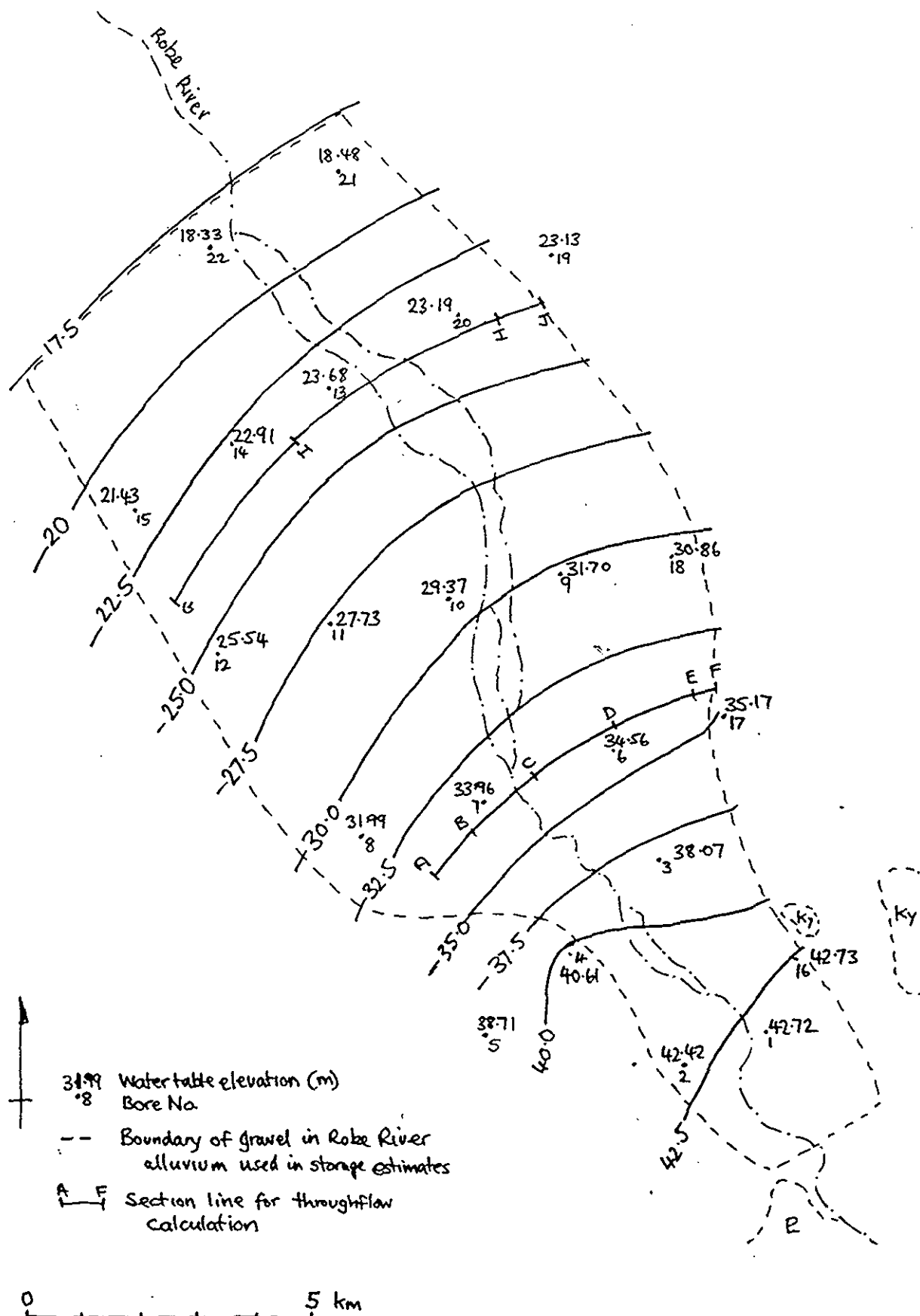
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	Initial	Date	FIG. 7: EXTENT AND ESTIMATED AGGREGATE THICKNESS OF ROBE RIVER ALLUVIUM	<div>Map Index</div> <div></div> <div>SF 50-6</div>
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Apvd				
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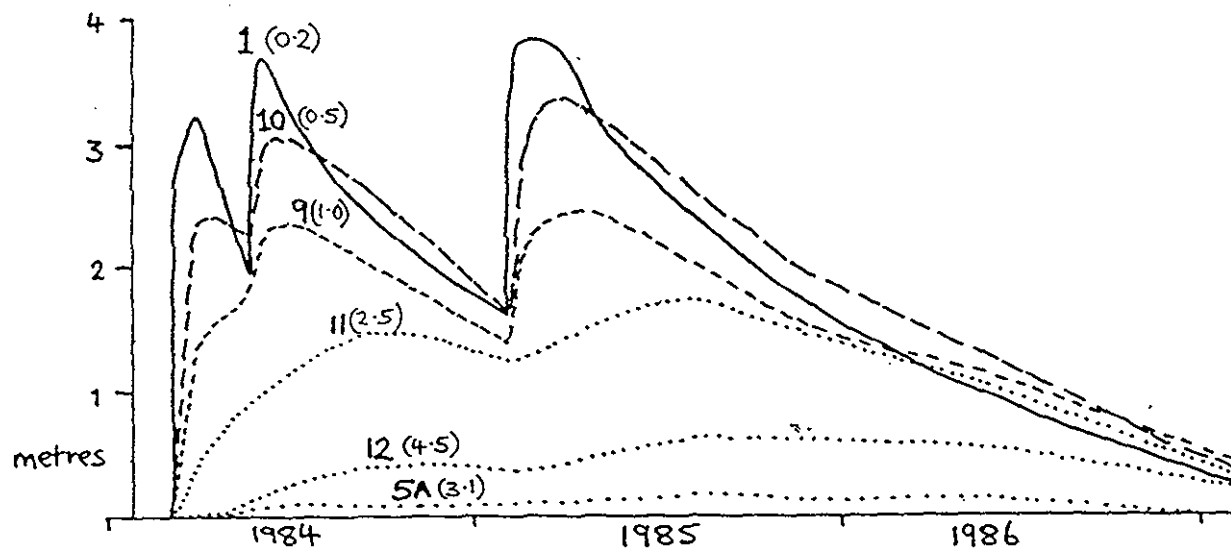
FIG. 8: WATER TABLE ELEVATION
(12 NOVEMBER 1985)

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SA Bore No. (3.1) Distance of bore from Robe River in km.

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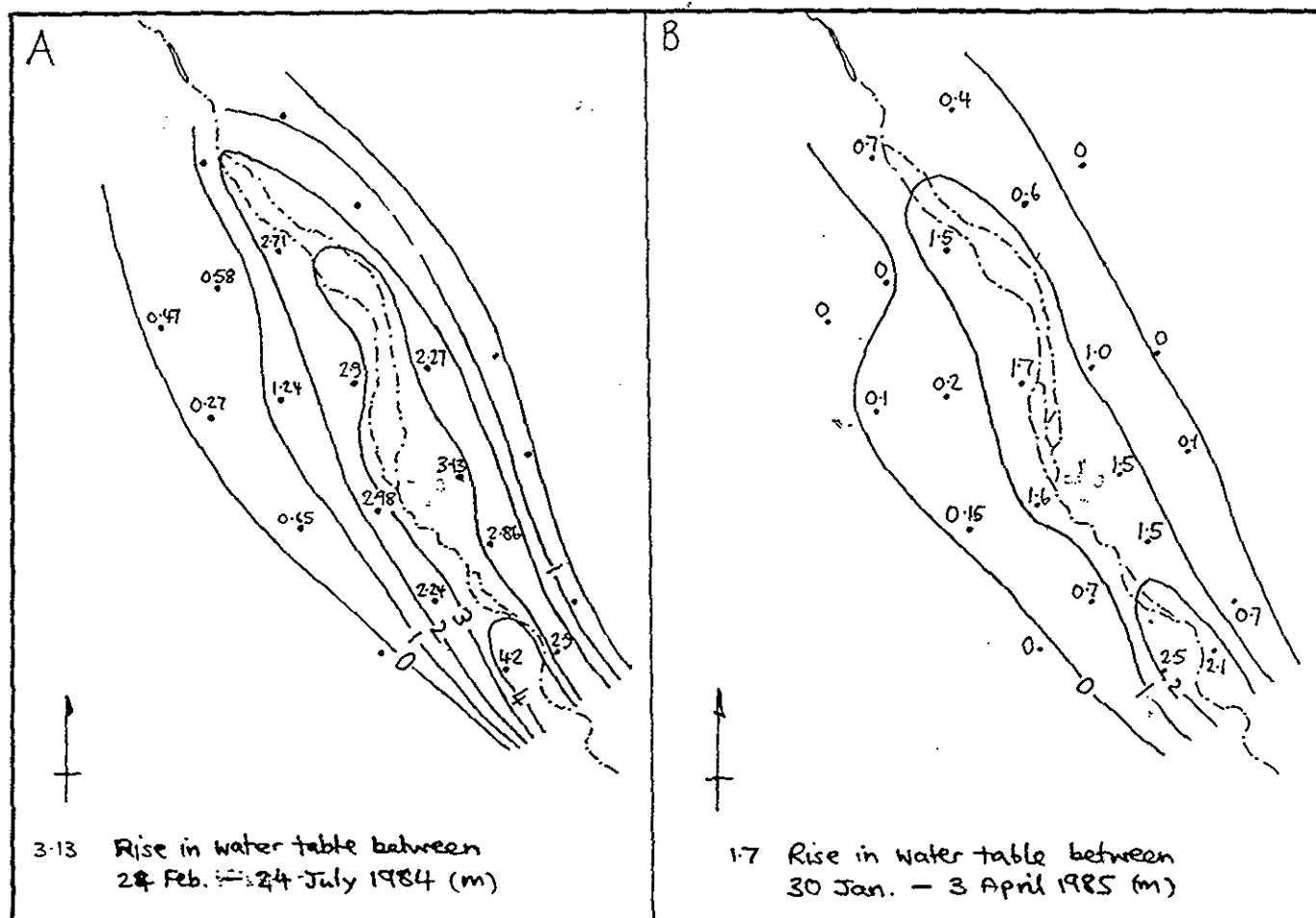
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FIG. 9: SELECTED HYDROGRAPHS SHOWING
WATER TABLE CHANGE FROM LEVEL
IMMEDIATELY PRECEDING CYCLONE 'CHLOE'

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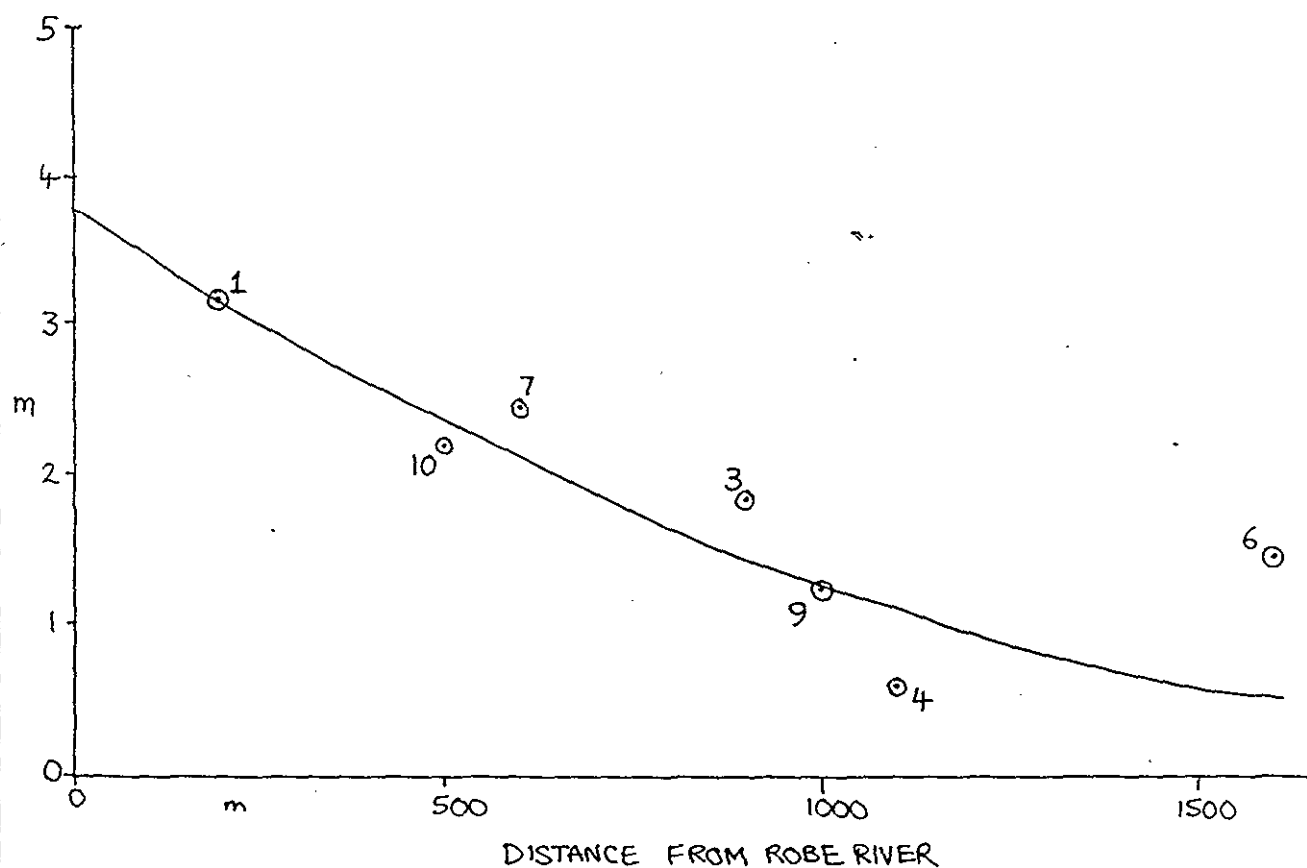
FIG. 10: RISE IN WATER TABLE:
A. FOLLOWING CYCLONE 'CHLOE',
B. FOLLOWING CYCLONE 'GERTIE'

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RISE IN WATER TABLE
30 DAYS AFTER FIRST
FLOW ON 2.3.84



○¹ GSWA bore number - observed water table rise
— calculated water table rise (Gill, 1985)

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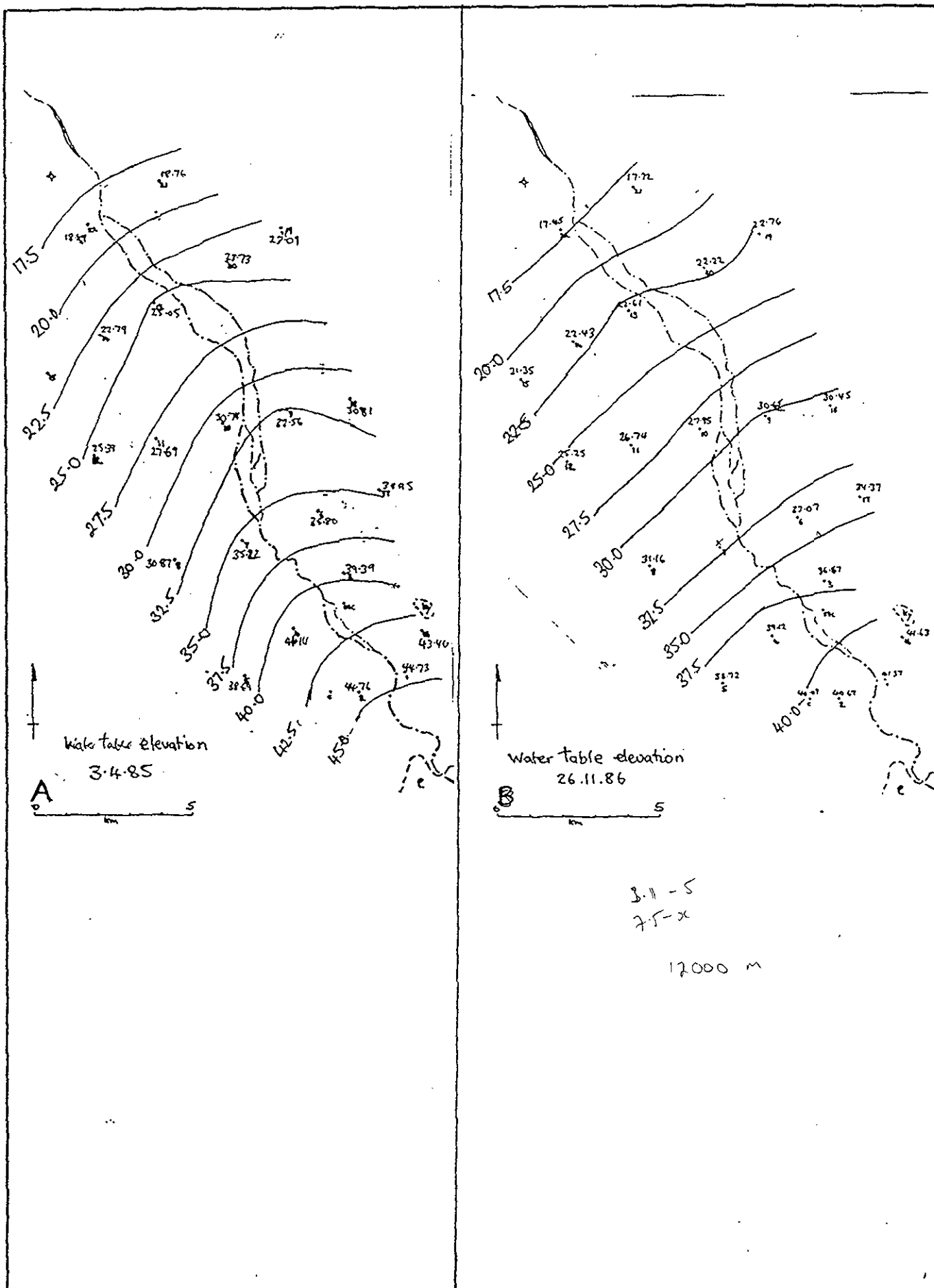
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FIG. 11: RELATIONSHIP BETWEEN WATER TABLE
RISE 30 DAYS AFTER FLOW AND DISTANCE
FROM THE ROBE RIVER

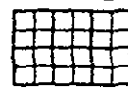
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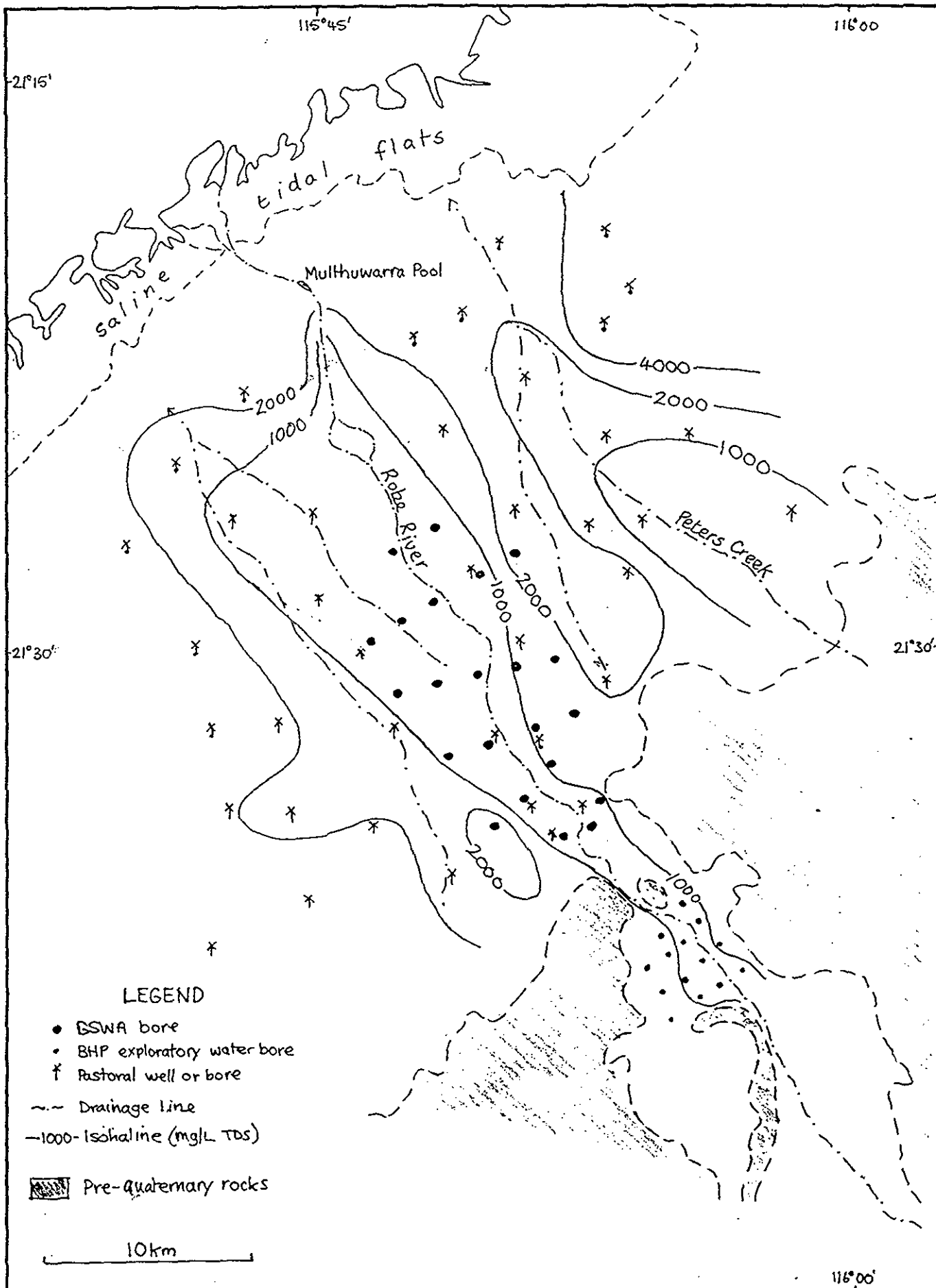


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	INITIAL	DATE	FIG. 12: WATER TABLE ELEVATION: A. MAXIMUM ;B. MINIMUM	MAP INDEX
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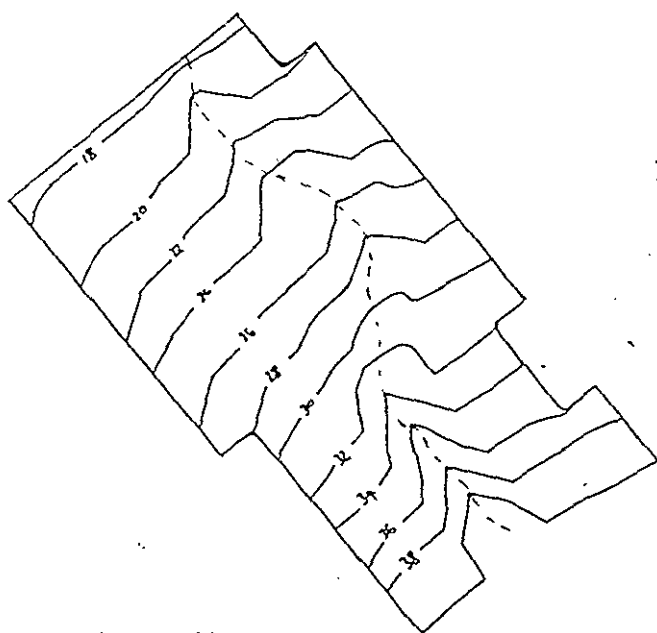
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FIG. 13: REGIONAL GROUNDWATER SALINITY
IN THE COASTAL PLAIN ALLUVIUM

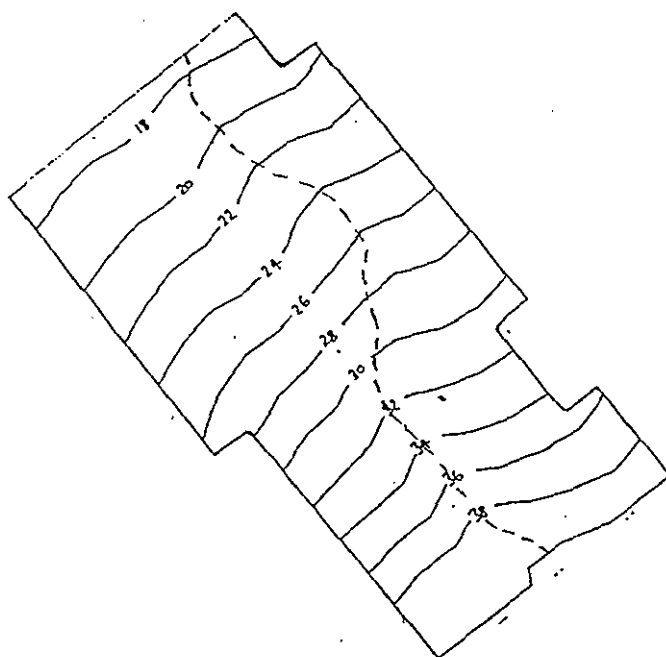
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A 1 month



B 11 months

0 1 2
km

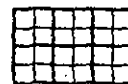
GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

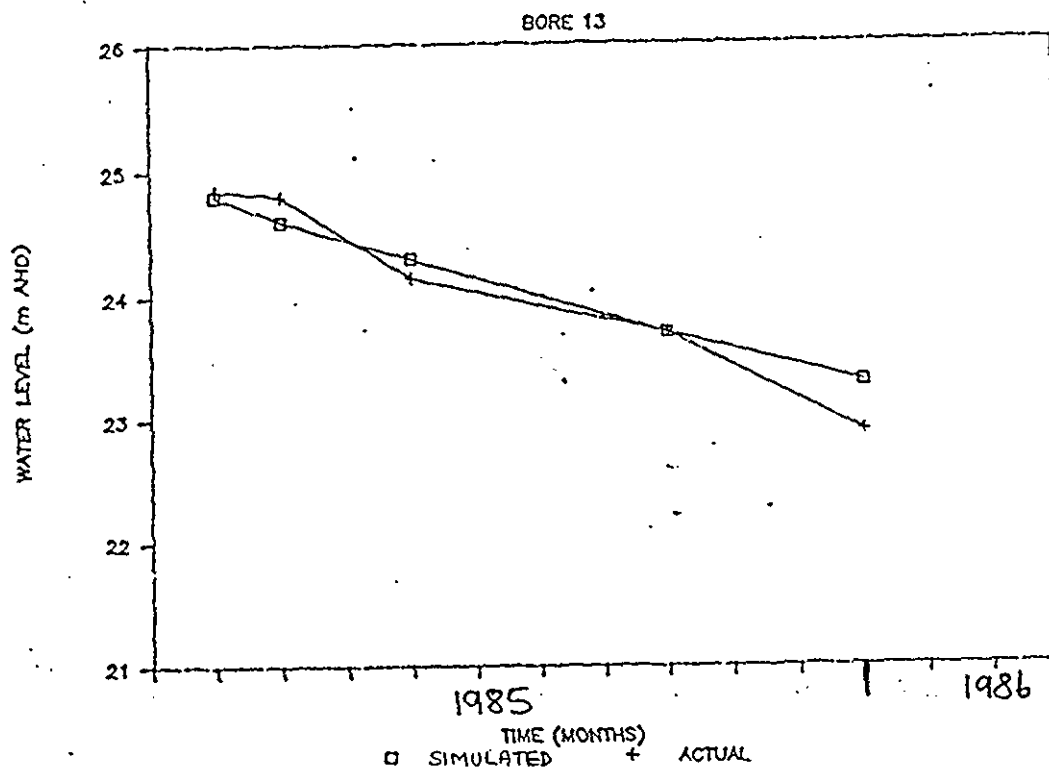
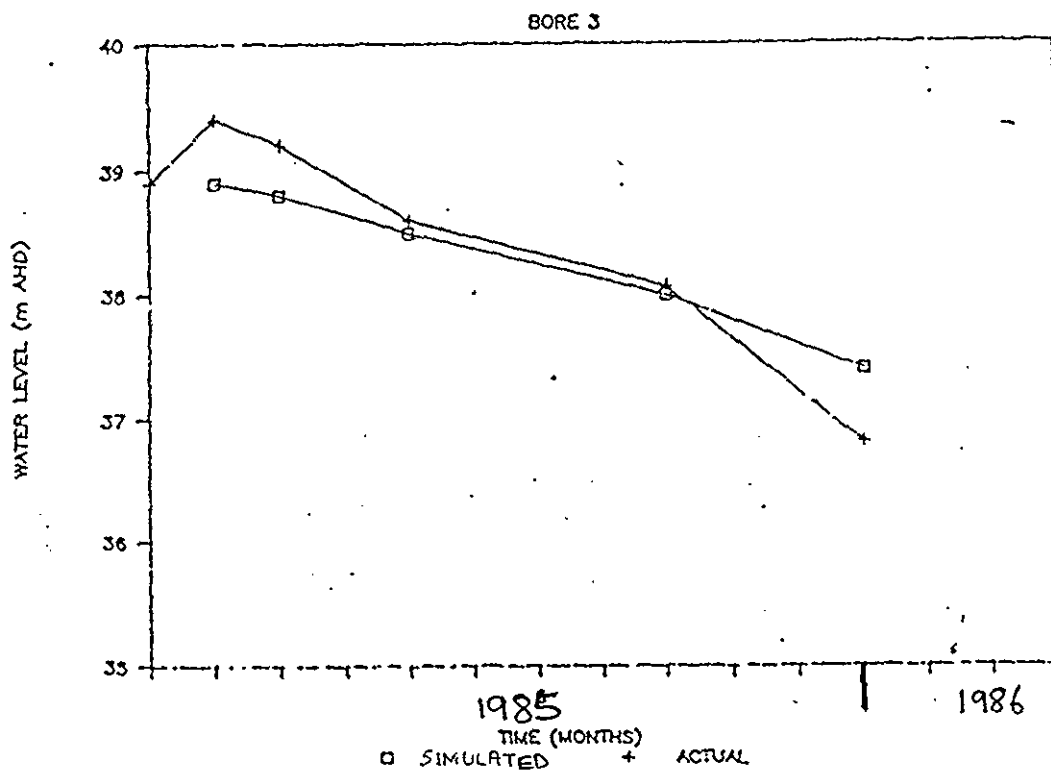
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FIG. 14: SIMULATED WATER TABLE ELEVATION
1 MONTH AND 11 MONTHS AFTER RECHARGE

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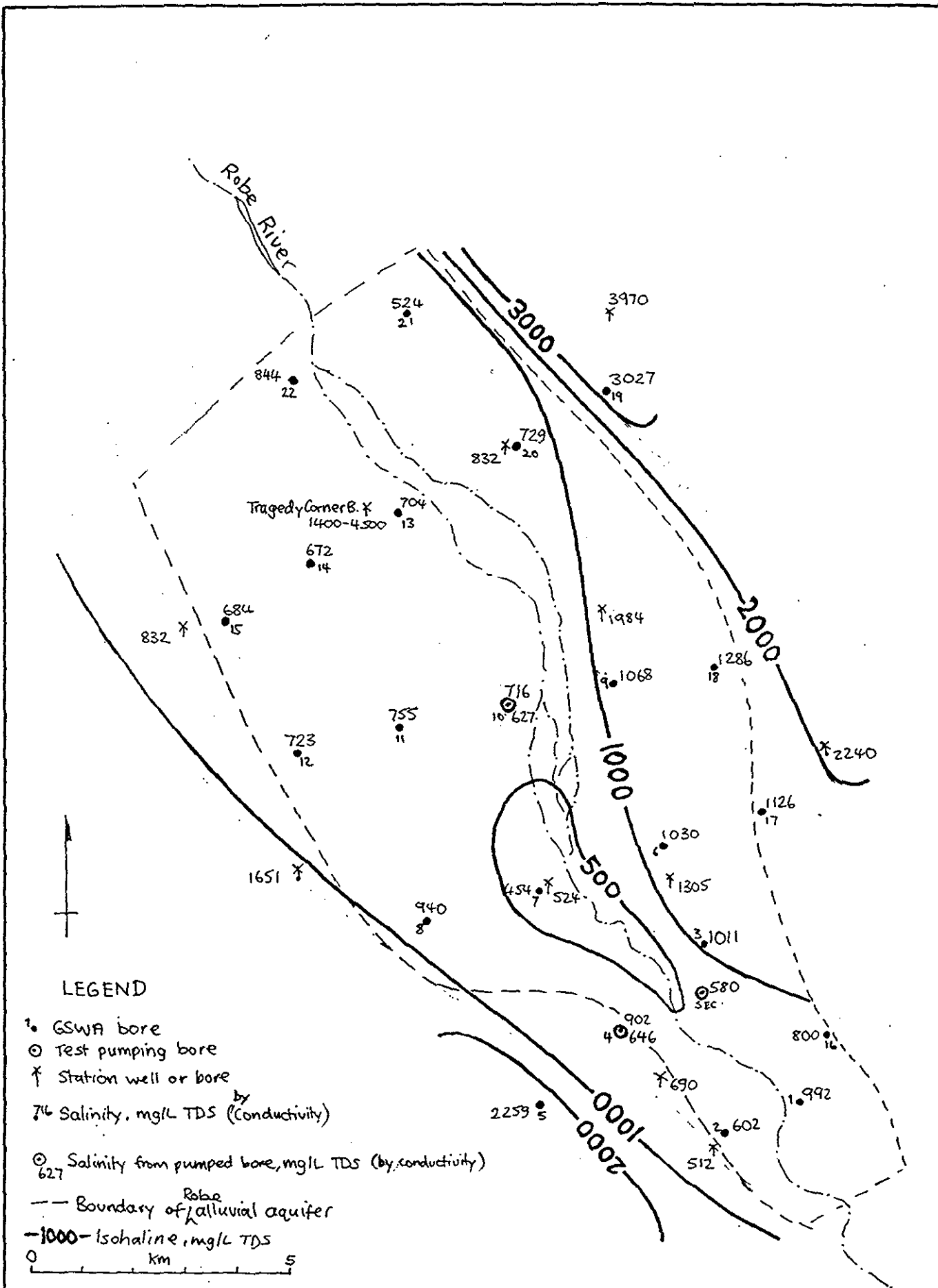
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FIG. 15: COMPARISON OF SIMULATED AND
ACTUAL WATER TABLE LEVELS

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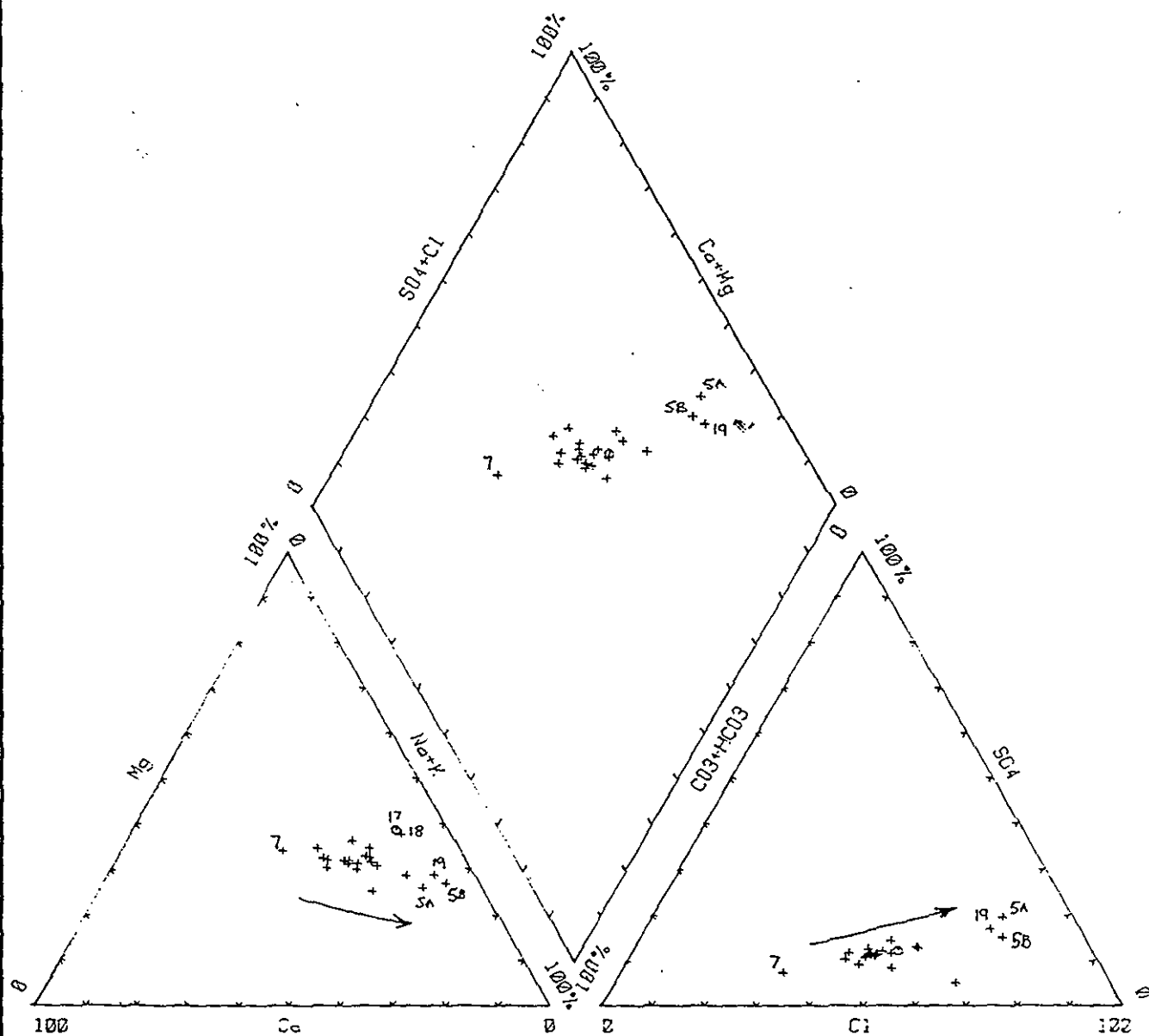
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FIG. 16: GROUNDWATER SALINITY IN THE ROBE RIVER ALLUVIUM AND TREALLA LIMESTONE

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7 Bore No.
 → Increasing salinity

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FIG. 17: PIPER TRILINEAR DIAGRAM OF
 CHEMICAL ANALYSES



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