THE BUNBURY SHALLOW-DRILLING GROUNDWATER INVESTIGATION

by D. P. Commander

ABSTRACT

The Bunbury shallow-drilling project extended over an area of about 600 km^2 within the southern Perth Basin. Pairs of bores consisting of a deep bore (about 100 m) and a shallow bore (less than 20 m) were drilled at twenty-six sites to investigate the stratigraphy and hydrogeology, and to provide a network of bores for long-term monitoring of water levels and salinities. An additional five test-pumping bores were also drilled at selected sites.

The superficial formations (Quaternary) cover the coastal plain to a maximum depth of about 20 m. In the east they are relatively clayey, and the salinity locally exceeds 4 000 mg/L. They are used for on-farm domestic and stock water.

The underlying Leederville Formation (Lower Cretaceous) consists of interbedded sands and shales and has a maximum thickness of 354 m in the axis of the Dardanup Syncline. The formation is recharged directly from rainfall on its outcrop on the Blackwood Plateau and groundwater flow is in a northerly direction, discharging to the sea near Leschenault Inlet. The salinity ranges from 300 to 700 mg/L and the formation is used for town supply at Dardanup and Australind, and on a small scale for industry near Bunbury. Annual throughflow is estimated to be 11 million cubic metres.

The major groundwater resources of the area are in the Yarragadee Formation, which is predominantly sandy. Between 200 m and 900 m of the formation contain groundwater, most of which ranges in salinity from 200 to 400 mg/L. Estimated annual abstraction from the formation is 18 million cubic metres, compared with a throughflow of about 66 million cubic metres per year, derived from recharge to the south of the study area.

INTRODUCTION

LOCATION

The Bunbury shallow-drilling project was carried out within an area of about 600 km^2 in the southern Perth Basin 150 km south of Perth (Fig. 1). Bunbury (pop. 21 000) is a regional centre for the processing and export of agricultural and forestry products, and mineral sands.

Water supplies for Bunbury and the nearby towns of Australind, Boyanup, Capel, Donnybrook and Eaton, and also for industry, are drawn from local groundwater resources.

PURPOSE AND SCOPE

The Bunbury shallow-drilling project was carried out by the Geological Survey to investigate the geology and the hydrogeology of the aquifers in the Perth Basin to a depth of 100 m; to provide a network of monitoring bores to measure the natural water level and salinity variations in the aquifers; and to monitor the effects of groundwater abstraction in and near Bunbury.

CLIMATE AND LAND USE

The Bunbury area has a Mediterranean-type climate with hot dry summers and cool wet winters.

The average annual rainfall is 886 mm at Bunbury but it increases to about 1 000 mm along the Darling Scarp. Rainfall exceeds evaporation during the five months, May to September.

Much of the land on the coastal plain has been cleared for agriculture, and in the Dardanup area pastures are irrigated using water from the Wellington Dam, on the Collie River east of the Darling Scarp.

The uplands to the east remain largely uncleared and are covered by native eucalypt forest. Intensive vegetable and fruit growing is carried out in the Preston River valley, between Donnybrook and Boyanup.

PREVIOUS WORK

The occurrence of artesian water at Bunbury was reported by Maitland (1898), but little further information on groundwater was published until the 1960s when bores were drilled for town supply at Eaton and Capel, and for the titania refinery at Australind (Passmore, 1962; Emmenegger 1963 a, b, c).

Exploratory drilling in the area by the Geological Survey of Western Australia (GSWA) commenced in 1967 with the drilling of the western part of the

Quindalup Line (QL), described by Probert (1968), which was subsequently completed in 1979-80 (Wharton, 1980).

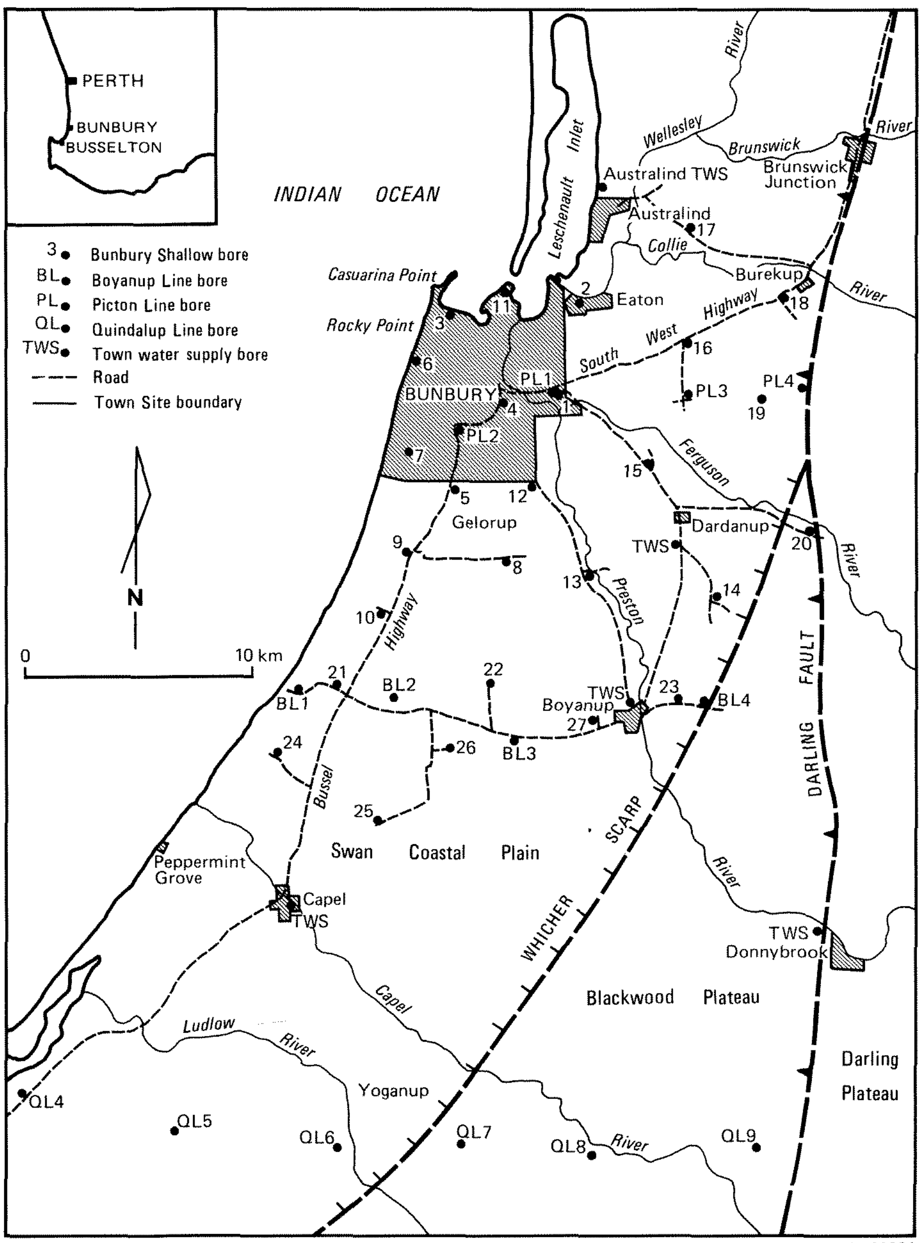
As a result of concern that overdrawing of the aquifers in Bunbury may have been taking place, a report on the hydrogeology with recommendations on a monitoring network was prepared by Whincup (1968). Subsequent reports by Barnes (1970) and Harley (1973) led to the drilling of Picton Line (PL) 1 bore in 1974 to a depth of 1 200 m. Three further Picton Line bores were completed in 1978 (Wharton 1980), and in 1981 four deep bores (Smith, pers. comm.) were drilled 13 km to the south along the Boyanup Line (BL).

The subsurface geology and hydrogeology of the city of Bunbury, including discussion of the effects of groundwater abstraction, has been described by Commander (1981).

DRILLING AND TESTING

The Bunbury shallow-drilling programme, which commenced in 1975 and completed in 1980, consisted of sixty-five bores at twenty-six sites, including shallow bores for monitoring the water table; deeper bores to a depth of about 100 m to monitor the confined aquifers; and five test-pumping bores to provide aquifer characteristics of the confined aquifers (Commander, 1976; Leech, 1977).

The bores were drilled by the Mines Department Drilling Section, using mud-rotary techniques. In bores where basalt was intersected, casing was run to the top of the basalt, and drilling continued with a



GSWA 20064

Figure 1. Locality and bore location map

down-hole hammer (air circulation) until the basalt was completely penetrated; then mud-rotary drilling was recommenced.

At each site, a bore was drilled to about 100 m (Table 1) and screened in a suitable sand. Galvanized iron-casing, 80 mm in diameter, was then inserted, usually with 80 mm in-line stainless-steel screens. In some bores, 50 mm or 40 mm telescoping screens were inserted after cement grouting, then 80 mm casing or blank casing was used and later perforated at the observation interval with explosive charges.

A shallow bore at each site was subsequently drilled and screened just below the water table, or where there was clay at the surface in the shallowest sand. At one site (BS4) three bores were drilled to monitor the Leederville and Yarragadee Formations as well as the water table.

Strata samples were taken at 3 m intervals and are stored in the GSWA core library. Gamma-ray logs have been run in all the bores, some prior to casing (in conjunction with resistivity logs) and others after casing.

Development and sampling of the bores was by air-lifting, and the water samples were analysed by the Government Chemical Laboratories (Table 2).

All the bores have been levelled to Australian Height Datum (AHD) by the Mines Department Surveys and Mapping Division or by the Public Works Department (PWD).

Since the completion of the bores, water levels have been monitored by the Public Works Department, and bore hydrographs collated in reports by Boyd (1979) and Ventriss and Boyd (1981).

Pumping bores were drilled at seven sites selected by Leech (1977). Of these sites only five were tested.

A pumping bore drilled at BS27 encountered basalt at the depth screened by BS27A, thus preventing aquifer testing, and at BS25 testing was abandoned when the screen lodged within the casing and could not be retrieved.

The pumping bores were located 30 to 50 m from the exploratory bore, which was used for observation during the pumping tests, and were cased with 155 mm steel casing with 6 metres of 100 mm-diameter stainless steel screen. A 100 mm-diameter electric submersible pump capable of a maximum pumping rate of 1 208 m^3/d was used. Step drawdown-tests were carried out to determine the bore efficiency followed by a constant-rate pumping test of up to 8 hours duration (Table 3).

Transmissivities and storage coefficients were calculated by matching drawdown-time data from the observation bore to standard type curves (Table 3).

PHYSIOGRAPHY

The area consists of a coastal plain about 15 km wide, separated from inland plateaux by erosional scarps.

LANDFORMS

Blackwood Plateau

The Blackwood Plateau (Playford and others, 1976) is bordered in the east by the Darling Scarp, which separates it from the Darling Plateau; and in the west by the Whicher Scarp, which has resulted from marine erosion and forms the boundary to the Swan Coastal Plain (Fig. 1). The plateau is a dissected lateritized surface, developed on Cretaceous sediments, and reaches a maximum elevation of about 160 m.

Swan Coastal Plain

The Swan Coastal Plain (McArthur and Bettenay, 1974) is bounded in the east by the Whicher and Darling Scarps (Fig. 1). It can be subdivided into a number of physiographic units consisting of an alluvial plain (Pinjarra Plain) in the east, with low irregular sand dunes (Bassendean Dunes) on its western margin; and a coastal belt, extending up to 7 km inland, of parallel ridges (Spearwood and Quindalup Dunes) with interdunal swamps, lagoons and inlets.

Rocky Point and Casuarina Point, on the coast at Bunbury, are formed by outcrops of basalt.

DRAINAGE

The area is drained by rivers flowing from the Darling Plateau, and by shorter streams which rise on the Blackwood Plateau and Darling Scarp. All drainage is into Leschenault Inlet (Fig. 1), with the exception of the Capel and Ludlow Rivers.

On the Pinjarra Plain there are numerous swamps, and in the Dardanup-Brunswick area drainage ditches have been constructed.

Most of the surface water flow is during winter in response to rainfall, but small base-flows in the summer are from groundwater discharge.

Key to Table 1 ▶

(a) below ground level
(b) "Superficial formations"

Q "Superficial formations"
Kl Leederville Formation
Juy Yarragadee Formation
AHD Australian Height Datum
TDS Total Dissolved Solids

TABLE 1. BOREHOLE DATA

Bore	Elevation Top Casing (m)	Total Depth (m)	Observation Interval (m)[a]	Aquifer [b]	Potentiometric Head (m) above AHD (10/12/80)	Salinity mg/L TDS conductivity x 6.4	Status
1A		90	—				Abandoned
1B	7.796	87	78-84	Kl	15	380	Observation bore
1C	7.781	19	12-18	Q	6.18	1 210	do
2A	2.609	98	91.5-97.9	Kl	-0.16	470	do
2B	2.209	6	0-6	Q	0.61	420	do
3A	1.353	100	94-100	Juy	0.23	350	do
3B	1.348	6	3-6	Q	-0.13	4 460	do
4A	8.444	80	80-81	Juy	1.44	420	do
4B	8.549	8	5-8	Q	5.91	540	do
4C	8.264	20	17-20	Kl	1.77	2 130	do
5A	8.046	110	99-105	Juy	4.84	770	do
5B	8.029	9	6-9	Q	4.72	510	do
6A	1.913	98	91.5-97.5	Juy	-0.87	630	do
6B	1.923	8	5-8	Q	0.37	8 190	do
7A	7.434	102	96-102	Juy	1.39	620	do
7B	7.564	12	6-12	Q	3.12	1 460	do
8A	24.420	106	99.5-105.5	Juy	6.12	380	do
8B	24.310	6	3-6	Q	21.36	200	do
9A	11.715	102	96-102	Juy	5.11	440	do
9B	11.730	12	6-12	Q	7.30	320	do
10A	10.457	102	—	Juy	5.71	250	Abandoned
10B	10.557	12	6-12	Q	6.43	860	Observation bore
10C	—	77	70.8-76.8	Juy	—	—	Pump bore
10D	—	76	68-74	Juy	—	—	Observation bore
11A	—	66	—	—	—	—	Abandoned
11B	6.388	110	87-98.6	Juy	0.96	380	Observation bore
11C	6.224	18	15-18	Q/Kl?	0.99	42 100	do
12A	16.703	102	96-102	Kl/Juy	5.90	414	do
12B	16.718	5	2-5	Q	15.18	380	do
13A	24.180	84	77-82	Kl	23.28	760	do
13B	24.225	27	19.5-25.5	Kl	16.31	1 100	do
13C	24.210	72	47-50	Kl	22.42	400	do
14A	42.943	98	79-85	Kl	29.46	520	do
14B	43.088	21	18-21	Kl	33.34	305	do
14C	—	85	79-85	Kl	—	—	Pump bore
15A	19.437	93	69-75	Kl	19.43	280	Observation bore
15B	19.492	19	13-19	Q	18.99	2 080	do
16A	14.428	99.6	74-80	Kl	13.38	290	do
16B	14.538	18	15-18	Q	13.74	2 810	do
16C	—	80	74-80	Kl	—	—	Pump bore
17A	13.580	108	75-81	Kl	8.58	330	Observation bore
17B	13.705	17	14-17	Q	7.50	1 250	do
18A	18.887	100	76-82	Kl	12.84	510	do
18B	18.972	15	12-15	Q	13.41	4 970	do
18C	—	82	76-82	Kl	—	—	Pump bore
20A	47.410	103	55-67	Kl	26.99	420	Observation bore
20B	47.505	19	15-18	Kl	42.82	2 240	do
21A	14.025	105	84-90	Juy	6.51	350	do
21C	13.526	25	18-24	Juy	4.42	880	do
22A	25.171	100	77-83	Juy	8.79	—	do
22B	25.168	15	9-15	Q	21.66	1 200	do
22C	—	83	77-83	Juy	—	820	Pump bore
23A	39.496	96	84-90	Kl	34.86	700	Observation bore
23B	39.548	20	15-18	Q	35.29	170	do
24A	2 602	18	13-16	Kl	0.8	790	Observation bore
24B	2.978	106	92-97	Kl/Juy	6.2	290	do
25A	15.873	100	89-95	Kl/Juy	12.31	490	do
25B	15.919	15	12-15	Q	15.34	1 720	do
25C	—	95	86-92	Kl/Juy	—	—	Abandoned
26A	21.641	100	90-96	Juy	8.09	1 110	Observation bore
26B	21.884	15	12-15	Q/Juy	19.48	1 110	do
27A	36.280	100	77-83	Kl	30.78	690	do
27B	36.261	25	19-25	Kl	30.52	1 220	do
27C	—	86	—	—	—	—	Abandoned
27D	—	85	76-85	Kl	—	—	do

TABLE 2. CHEMICAL ANALYSES OF WATER SAMPLES

Bore	TDS C x 6.4	Hardness	Mineral matter in mg/L						
			Ca	Mg	Na	K	Cl	SO_4	HCO_3
					Superficial Formations				
BS1C	1 209	105	6	22	345	8	443	158	94
BS2B	416	74	10	12	88	10	140	42	44
BS3B	4 460	906	129	142	1 160	52	1 970	246	549
BS4B	537	78	10	13	136	4	193	11	116
BS5B	505	255	43	36	56	7	55	280	20
BS6B	8 192	1 569	179	273	2 260	79	4 040	550	377
BS7B	1 459	400	91	42	299	6	498	85	290
BS8B	204	25	2	5	48	4	76	11	19
BS9B	320	56	6	10	72	3	117	13	46
BS10B	864	179	34	23	195	7	342	21	128
BS11B	42 100	8 800	641	1 750	14 100	455	25 700	3 390	323
BS12B	384	99	25	9	75	18	90	19	169
BS13B	1 100	184	8	40	251	9	461	46	51
BS14B	307	61	8	10	54	3	86	19	79
BS15B	2 080	283	36	47	485	3	880	22	98
BS16B	2 809	497	33	101	715	7	1 350	97	70
BS17B	1 254	311	34	55	267	11	522	90	90
BS18B	4 966	1 208	79	246	1 200	10	2 490	230	104
BS20B	2 240	460	41	87	527	8	1 020	87	101
BS21C	883	166	14	32	199	8	383	39	37
BS22B	1 241	195	6	44	257	5	497	68	8
BS23B	166	14	1	3	43	2	55	21	15
BS24B	288	76	19	7	49	19	58	8	150
BS25B	1 721	272	12	59	458	8	850	67	
BS26B	1 107	217	18	42	260	3	501	34	55
BS27B	1 216	217	18	42	290	5	528	69	49
					Leederville Formation				
BS1B	377	62	7	11	75	14	129	20	48
BS2A	473	118	31	10	94	13	131	14	171
BS4C	2 131	413	60	64	524	13	886	123	234
BS13A	755	154	14	29	117	18	328	24	0
BS13C	396	58	2	13	85	14	160	20	18
BS14A	518	81	8	15	117	7	210	17	38
BS15A	275	48	8	7	57	9	92	11	52
BS16A	294	46	7	7	62	10	101	13	46
BS17A	332	56	8	9	72	12	106	15	79
BS18A	512	158	32	19	82	14	187	8	101
BS20A	422	80	6	16	82	13	174	15	18
BS23A	697	148	25	21	143	15	257	40	102
BS27A	691	182	32	25	139	11	279	36	85
					Yarragadee Formation				
BS3A	352	95	25	8	55	31	79	14	156
BS4A	422	100	19	13	79	21	134	18	112
BS5A	768	158	29	21	173	7	306	28	101
BS6A	627	127	13	23	126	13	265	27	20
BS7A	620	99	20	12	144	13	239	26	79
BS8A	377	83	12	13	68	18	123	17	78
BS9A	435	62	12	8	101	7	167	5	61
BS10A	249	42	7	6	48	19	64	17	76
BS11B	377	83	17	10	74	14	118	14	99
BS12A	416	121	37	7	68	18	102	16	152
BS21A	345	84	19	9	65	20	82	21	142
BS22C	819	134	6	29	215	5	386	37	27
BS24A	787	170	47	13	188	6	264	29	211
BS25A	486	83	7	16	105	15	194	22	43
BS26A	1 107	161	7	35	274	9	498	49	18

TABLE 3
PUMPING-TEST RESULTS

Boresite	Pump Rate m^3/d	Aquifer	Transmissivity m^2/d	Hydraulic Conductivity m/d	Storage Coefficient x 10^{-4}
BS10	1 208	Yarragadee	109	18	2.0
BS14	89	Leederville	40	(a) 13	2.4
BS16	1 080	Leederville	88	14	10
BS18	1 118	Leederville	130	21	2.4
BS22	670	Yarragadee	15	(b) 2.5	1.5

(a) Screened interval partially in clay, 3 m operative length assumed.
(b) This result is low, possibly due to poor hydraulic connection between bores.

GEOLOGY

SETTING

The Bunbury area lies within the southern Perth Basin in the Bunbury Trough (Playford and others, 1976), which contains up to 8 000 m of sediments, bounded on the east by the Darling Fault and the Precambrian crystalline rocks of the Yilgarn Block.

The near-surface stratigraphic succession for the Bunbury area is given in Table 4.

STRATIGRAPHY

Cockleshell Gully Formation

The Cockleshell Gully Formation was not encountered in the Bunbury shallow bores but has been intersected by deep bores in the Boyanup and Picton Lines (Smith, pers. comm; Wharton 1980, 1981). A thickness of 634 m was penetrated in Picton Line 1, although the maximum thickness is believed to be about 1 500 m (Playford and others, 1976).

The formation consists of fine to granular, moderately sorted, weakly consolidated quartz sand with accessory garnet and pyrite, which is interbedded with grey silty-shale and carbonaceous shale in beds up to 12 m thick, often containing beds of soft lignite. It is a continental deposit of Early Jurassic age.

Yarragadee Formation

The Yarragadee Formation conformably overlies the Cockleshell Gully Formation. It subcrops beneath the Bunbury Basalt or the Leederville Formation, and beneath the superficial formations in a small area south of Bunbury (Fig. 2), and was intersected at 18 sites.

The formation is probably about 1 300 m thick in the axis of the Bunbury Trough, however the maximum thickness intersected was 1 115 m, in QL9 (Wharton, 1981). The formation thins northwards to 187 m in PL2 (Wharton, 1980), owing to removal of the upper part by erosion.

TABLE 4
STRATIGRAPHY OF THE BUNBURY AREA

Age	Formation	Maximum Thickness (m)	Lithology
CAINOZOIC			
Quaternary			
(Holocene)	Safety Bay Sand	70	Sand
(Pleistocene)	Tamala Limestone	50	Limestone, sand
	Bassendean Sand	20	Sand
	Guildford Formation	25	Clay, sand
Pliocene?	Yoganup Formation	20	Sand
	UNCONFORMITY		
MESOZOIC			
Cretaceous	Leederville Formation	380	Sand, siltstone, shale
(Lower)	Bunbury Basalt	85	Basalt, in places weathered to clay
	UNCONFORMITY		
Jurassic	Yarragadee Formation	1 300	Sand, minor shale
(Upper-Middle)			
(Lower)	Cockleshell Gully Formation	1 500	Sand and Shale

The formation is composed of interbedded sand, shale and siltstone. The basal part of the formation is predominantly sand, but the proportion of sand decreases to 25 per cent in the upper 500 m in QL9 (Wharton, 1981).

The sand is predominantly pale-grey quartz, ranging from fine sand to fine gravel with moderate to good sorting, and is weakly consolidated. Layers containing heavy minerals and pyrite are common.

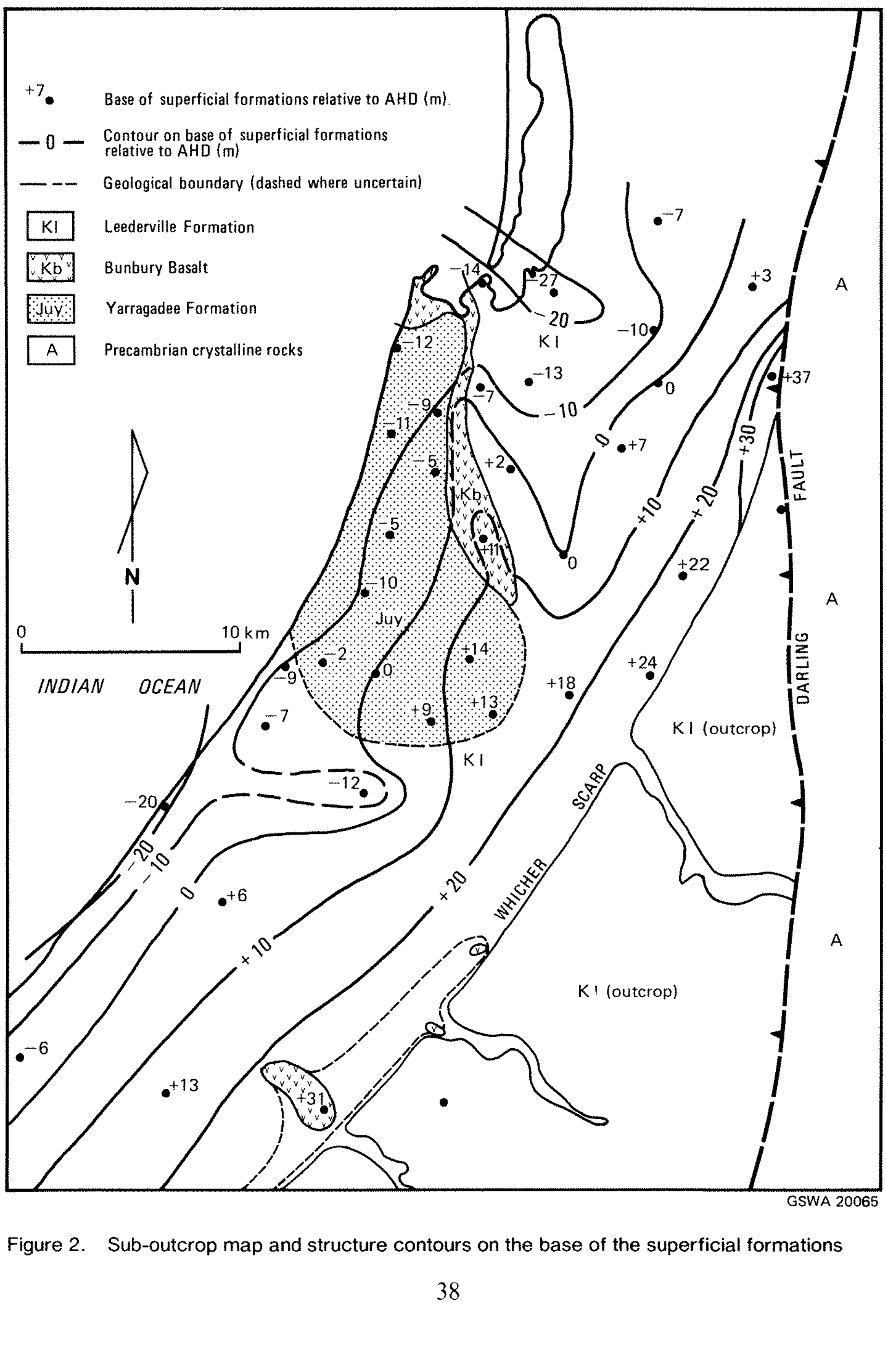
The shale is dark-grey to brown-grey, slightly silty or sandy and moderately consolidated. Carbonaceous material is common, ranging from carbonaceous shale to hard, vitreous coal, occurring in lenses and seams rarely up to 2 m thick (Wharton 1980).

Near Bunbury, where the Yarragadee Formation is directly overlain by Bunbury Basalt and by the superficial formations, the shales are weathered yellow and the sand grains coated with yellow iron-oxides.

The formation was laid down in a continental environment, and ranges in age from Middle to Late Jurassic.

Bunbury Basalt

The Bunbury Basalt unconformably overlies the Yarragadee Formation and is overlain by the Leederville Formation. It crops out between Rocky Point and Casuarina Point at Bunbury and is



GSWA 20065

Figure 2. Sub-outcrop map and structure contours on the base of the superficial formations

exposed in the Gelorup quarry and mineral-sand pits at Yoganup (Burgess, 1978; Wharton 1981). In the subsurface it occurs as a sinuous body extending northwards from Yoganup to Boyanup and Bunbury (Fig. 5). Its presence can be determined locally by ground-magnetic surveys and inferred regionally from the aeromagnetic data (Bureau of Mineral Resources, 1960).

The basalt is described as a porphyritic tholeiitic basalt (Trendall, 1962; Burgess, 1978; Wilde and Walker, 1979). In outcrop it is fresh and displays columnar jointing, but in the subsurface, the top and bottom of the basalt are commonly weathered to a chocolate-brown or bluish clay. In places, the full thickness of basalt is altered, as in PWD Eaton 1 where the clay is 24 m thick (Emmenegger, 1963b); weathered horizons also occur within the basalt and Trendall (1962) has described a scoriaceous horizon in the Sunnywest Boyanup bore separating distinct "flows" (Fig. 3). Sand and sedimentary clays have also been reported from within the basalt and such a clay from QL6 may be of Early Cretaceous age (Wharton, 1981).

The maximum thickness intersected by drilling in the area is 85 m at Boyanup, but the thickness may change rapidly in a short distance. Drilling at BS27 has shown that the top of the basalt differs in elevation by at least 24 m in bores only 50 m apart, and in Bunbury the thickness increases by 50 m between BS24 and the Bunbury Water Board (BWB) Robertson bore, a distance of n.p. 200 m.

Coastal erosion prior to the deposition of the superficial formations in Bunbury has formed steep cliffs of basalt which have subsequently been covered by Tamala Limestone or Safety Bay Sand, except on the beach at Casuarina and Rocky Points. The position of these cliffs is known from borehole evidence within Bunbury (Commander, 1981).

The basalt is postulated to be either a number of surface flows from a source near the Darling Fault deposited in deeply incised valleys (Lowry, 1965), or the result of extrusion along fault lines (Burgess, 1978). Evidence from boreholes for either origin is inconclusive, but the rapid changes in thickness and the position of the basalt along the possibly faulted western margin of the Dardanup Syncline (Fig. 3; Fig. 4), could be more readily explained as the result of extrusion from several centres along a fault line within the Perth Basin.

Leederville Formation

The Leederville Formation rests unconformably on the Yarragadee Formation and the Bunbury Basalt. It crops out on the Blackwood Plateau, where it has been lateritised to a massive laterite and pisolitic gravel; on the coastal plain it is covered by the superficial formations. The formation is thickest in the Dardanup Syncline (Fig. 4) and the maximum known thickness of 384 m was penetrated in QL9 (Wharton, 1981).

The formation consists of interbedded sand, siltstone and shale, with rare conglomerate and coal seams. It can be broadly divided into a lower predominantly shaley section, and an upper sandy section, but individual beds are not persistent and cannot be correlated with certainty between boreholes.

The sands are composed of weakly consolidated, poorly to moderately sorted, fine- to very coarse-grained quartz with accessory feldspar and heavy minerals. The siltstones and shales are generally dark grey, brown grey and grey green, micaceous and commonly carbonaceous and pyritic. Red clay which occurs in bores at the mineral sand mines near Capel may represent derived basaltic material at the base of the Leederville Formation.

Quartzite pebbles are common in the Boyanup-Dardanup area in a lower part of the formation, and Maitland (1913) describes a quartzite pebble bed, 25 m thick, in the Dardanup bore (Fig. 3).

Carbonaceous material ranges from carbonaceous shale and carbonised plant material to lignite, and occurs mainly as thin lenses or disseminated chips in shale; thin coal seams up to 1 m thick are indicated on wireline logs (Wharton, 1981).

Palynological analyses indicates that the formation is of Early Cretaceous age and was mostly laid down in a non-marine environment, with local marine and lagoonal sedimentation close to the present coastline.

Superficial formations

The superficial formations consist of a number of littoral, alluvial, eolian and estaurine sediments of Pliocene to Holocene age. They rest on a gently west-sloping unconformity surface on the coastal plain (Fig. 2) and extend up the main valleys in the Blackwood Plateau. The slope of the unconformity surface is broken by more resistant islands of Bunbury Basalt near Bunbury and Yoganup, and by a deeper channel at the mouth of the Collie River.

Yoganup Formation: The Yoganup Formation (Low, 1971) is a shore-line deposit along the base of the Whicher Scarp consisting of leached and ferruginized beach sand and conglomerate containing mineral sands (Baxter, 1977; Wilde and Walker, 1979).

The formation was encountered in BS23 where it is a medium to coarse quartz-sand with accessory heavy minerals and minor clay.

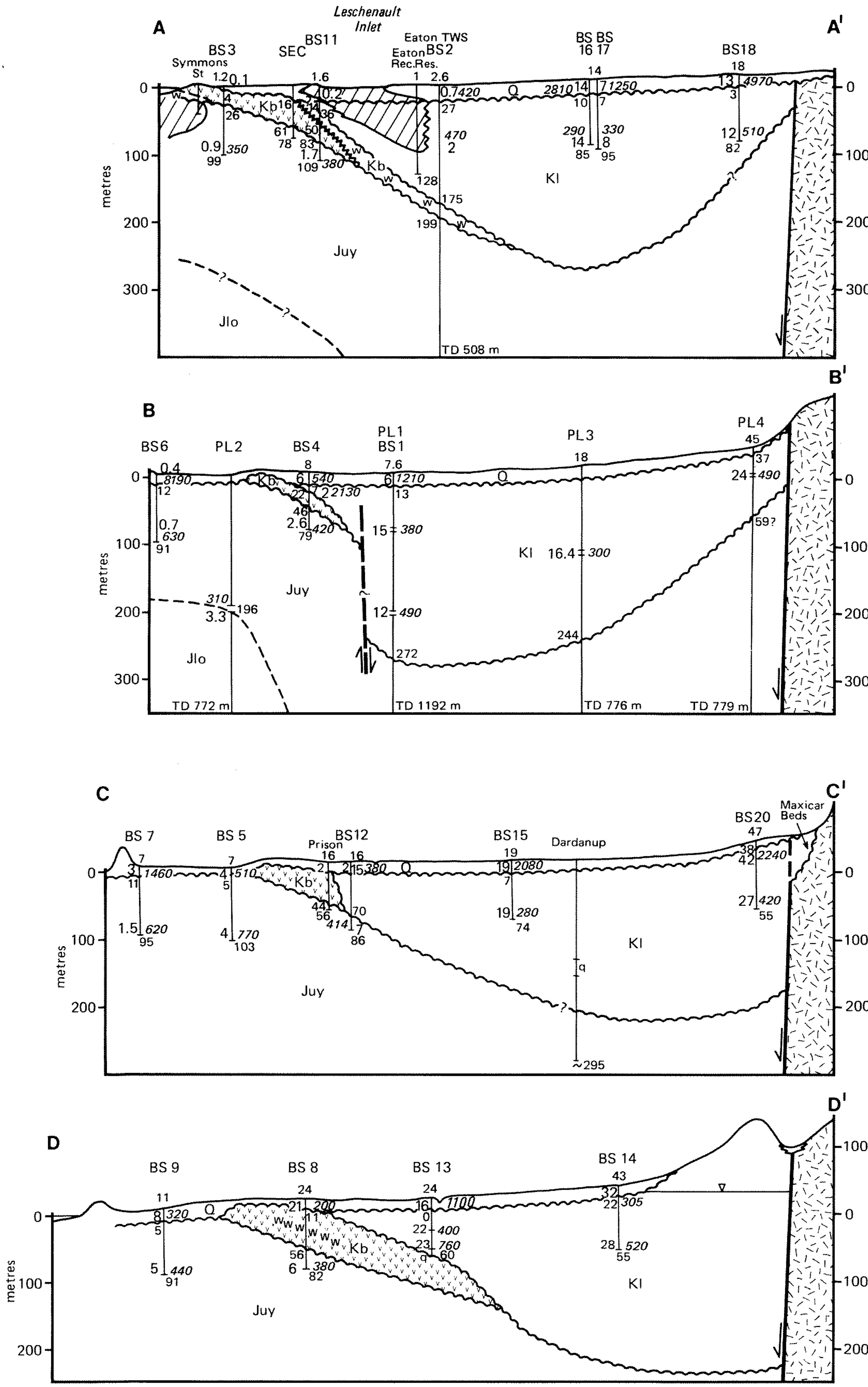
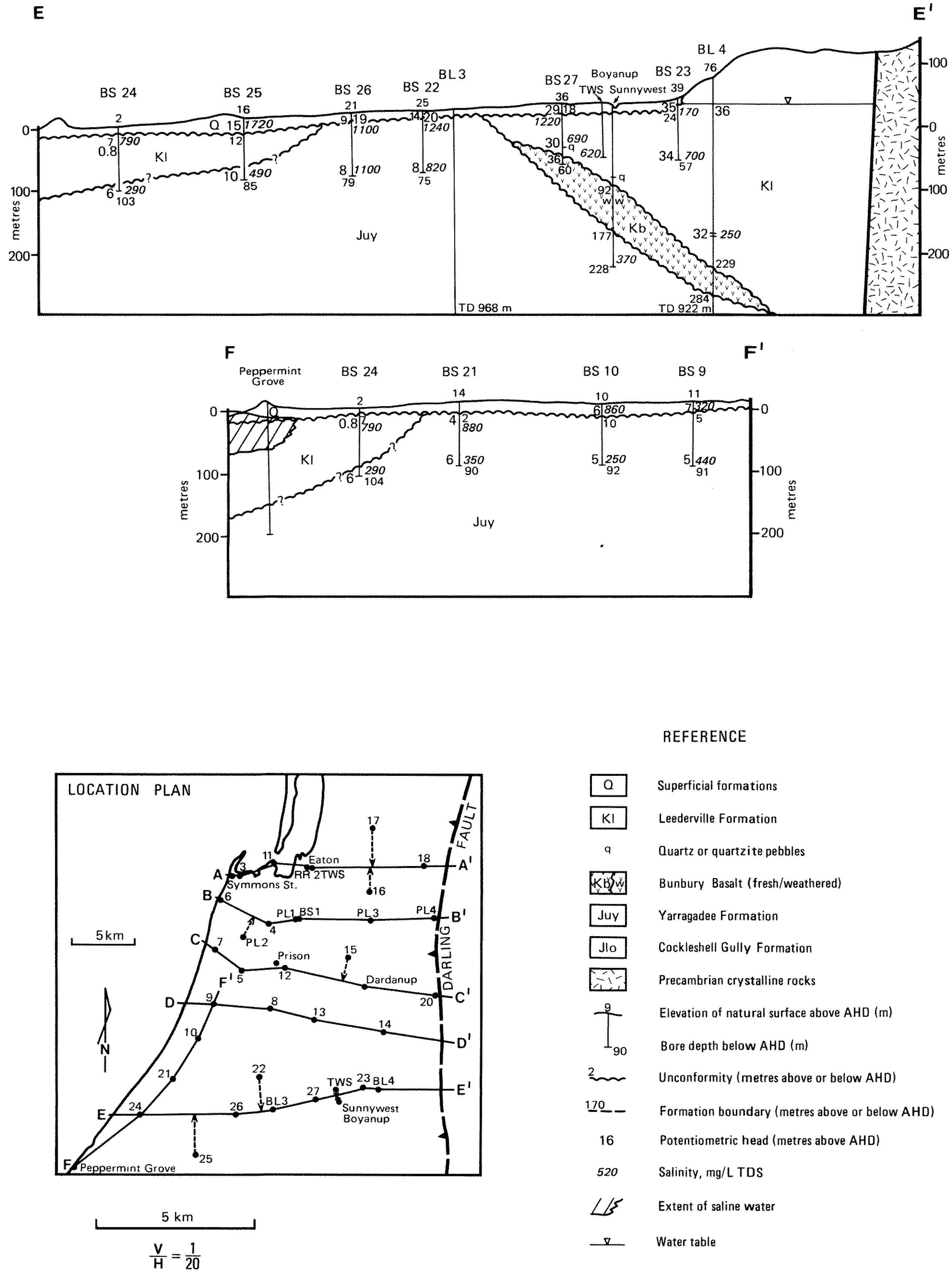


Figure 3. Hydrogeological cross-section


E
E'
BS 24
BS 25
BS 26
BS 22
BL 3
BS 27
Boyanup TWS
Sunnywest
BS 23
BL 4
Q
Kl
Juy
Kb
TD 968 m
TD 922 m
metres
F
F'
Peppermint Grove
BS 24
BS 21
BS 10
BS 9
Kl
Juy
metres
LOCATION PLAN
5 km
N
Eaton
RR 2TWS
Symmons St.
PL1
BS1
PL3
PL4
PL2
Prison
Dardanup
TWS
BL4
BL3
Sunnywest
Boyanup
Peppermint Grove
DARLING FAULT
A
A'
B
B'
C
C'
D
D'
E
E'
F
F'
5 km
V/H = 1/20
REFERENCE
Q Superficial formations
Kl Leederville Formation
q Quartz or quartzite pebbles
Kb w Bunbury Basalt (fresh/weathered)
Juy Yarragadee Formation
Jlo Cockleshell Gully Formation
Precambrian crystalline rocks
9 Elevation of natural surface above AHD (m)
90 Bore depth below AHD (m)
2 Unconformity (metres above or below AHD)
170 Formation boundary (metres above or below AHD)
16 Potentiometric head (metres above AHD)
520 Salinity, mg/L TDS
Extent of saline water
Water table

GSWA 20066

Guildford Formation: The Guildford Formation (Low, 1971) is an alluvial deposit extending westwards from the Yoganup Formation and underlying the Pinjarra Plain. Similar alluvium occurs in the valleys of the Ferguson, Preston, Capel and Ludlow Rivers within the Blackwood Plateau.

The formation consists mainly of brown, or dark-grey clay with thin beds of sand towards the base. It ranges in thickness from 15 m to 30 m.

Bassendean Sand: The Bassendean Sand (Playford and Low, 1972) is a series of dunes forming a discontinuous zone of low hills. The formation reaches a maximum thickness of about 20 m in the west, where it directly overlies Mesozoic sediments, and thins eastwards where it overlies, or interfingers with, the Guildford Formation.

The formation consists of medium- to coarse-grained white quartz sand, with mineral-sand deposits (Capel shoreline) at its base in the Capel area (Baxter, 1977).

Tamala Limestone: The Tamala Limestone (Playford and others, 1976) is an eolian calcarenite which forms elongated dunes in a 4-5 km-wide belt parallel to the present coastline. It extends from about 10 m below to about 48 m above sea-level and overlies the Yarragadee Formation, Bunbury Basalt and Leederville Formation. Its eastern margin is believed to overlie the Bassendean Sand. The formation ranges from coarse-grained unconsolidated quartz-sand to lithified calcarenite.

Safety Bay Sand: The Safety Bay Sand (Playford and others, 1976) is a narrow strip of vegetated and

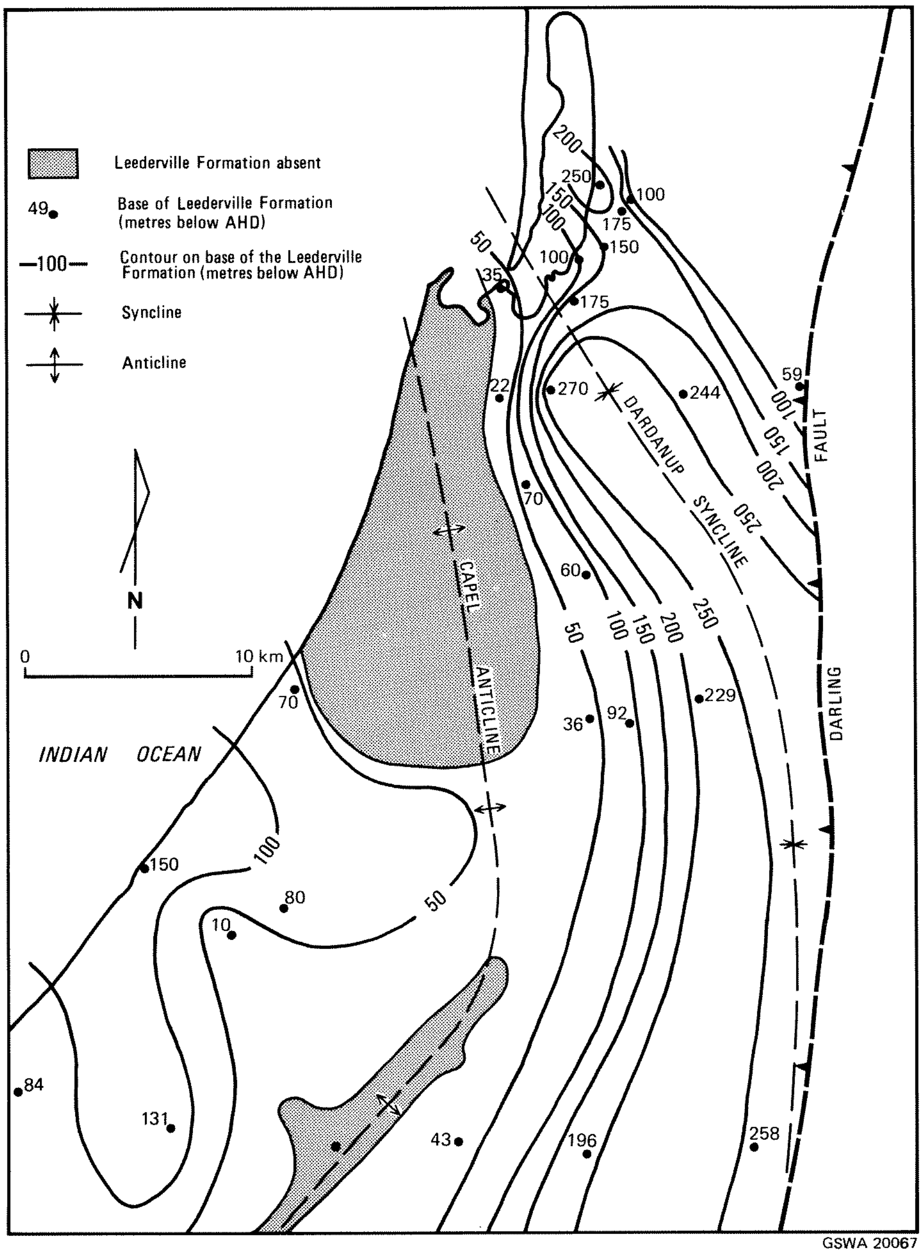


Figure 4. Leederville Formation; extent and structure contours on the base

mobile dunes, consisting of unlithified calcareous sand, along the coastline. It extends to 68 m above sea-level and overlies the Tamala Limestone, Bunbury Basalt, and alluvial and estuarine clays.

Miscellaneous alluvial and estuarine deposits: A number of black, brown, green and red clays intercalated with sands and calcarenites underlie the west of Bunbury (Commander 1976, 1981) and rest directly on basalt or Mesozoic sediments. These units presumably represent Quarternary alluvial or estuarine sediments, including clays reworked from weathered basalt.

Lagoonal muds separate the Safety Bay Sand and the Tamala Limestone beneath the peninsula, west of Leschenault Inlet (Barnes, 1974), and similar muds have been intersected in BS21 and BS24 where they directly overlie the Yarragadee or Leederville Formations.

Alluvium of Holocene age occurs along the rivers which traverse the coastal plain.

STRUCTURE

The structure of the area is illustrated by the geological sections (Fig. 3).

The Yarragadee and Cockleshell Gully Formations are east dipping and abut the Precambrian crystalline-rocks along the Darling Fault (Smith, pers. comm; Wharton 1980, 1981).

The Leederville Formation is gently folded so that its thickest development is in the Dardanup Syncline (Fig. 4), the axis of which parallels the Darling Fault

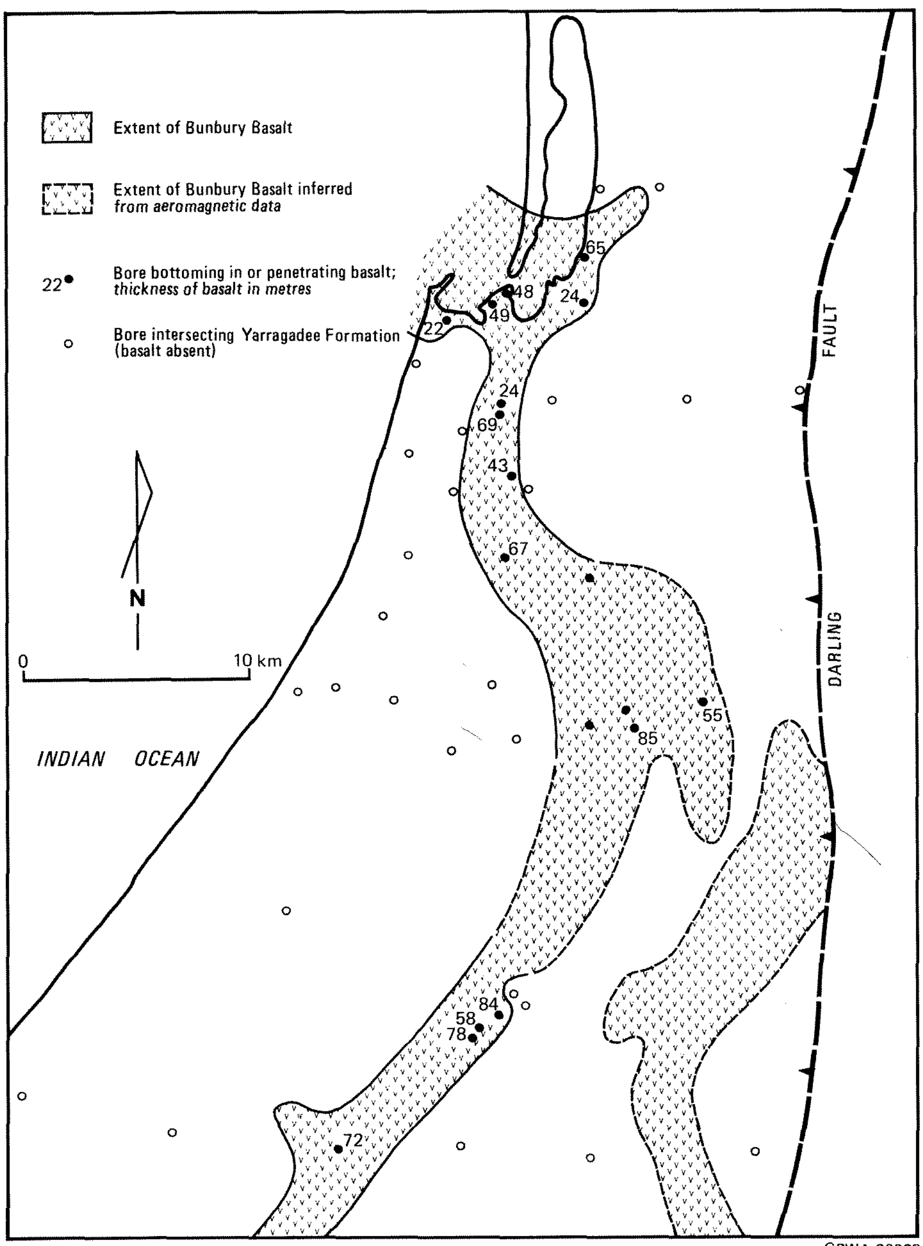


Figure 5. Distribution and thickness of the Bunbury Basalt

south of Donnybrook and trends northwestwards from Donnybrook to Eaton. The formation thins westwards where it has been eroded from the crest of the Capel Anticline (Fig. 4). The Dardanup Syncline and Capel Anticline are probably developed over fault blocks in the Jurassic sediments. It is possible that faulting extends into the Leederville Formation just west of PL2, where there is a steep apparent dip (Fig. 3, Cross-section BB).

HYDROGEOLOGY

AQUIFERS

Superficial Formations

Groundwater Flow: The superficial formations together form a relatively thin and predominantly clayey unconfined aquifer in which groundwater flow is generally in a westerly direction. However, vertical flow is significant in the areas of low relief on the Pinjarra Plain where there are often substantial vertical hydraulic-gradients in both upwards and downwards directions. Groundwater relationships between the superficial formations and the underlying aquifers are illustrated on Figure 6.

Recharge to the superficial formations (Fig. 7) is mostly from rainfall. Some recharge, by upward groundwater flow, takes place from the Leederville Formation in areas where there are upward hydraulic heads (Fig. 8).

Groundwater discharges to the ocean and the coastal swamps near Capel, to the Collie and Preston Rivers (as indicated by the water-table contours, Figure 7), and to drains in the Dardanup area. Discharge also takes place by direct evaporation from swamps and evapotranspiration from vegetation where the water table is shallow, especially in the Guildford Formation near Dardanup where detailed studies have shown the potential exists for upward groundwater-flow (George, 1980). Groundwater flow from sandy superficial formations into the Yarragadee and Leederville Formations occurs where the hydraulic head is downwards at BS 5, 7, 9 and 10, and to a lesser extent BS 22, 25 and 26 where the strata are more clayey (Fig. 8).

The average seasonal variation in the elevation of the water table (Fig. 8) is about 1 m, but is lower (0.3-0.6 m) in sandy sediments near the coast, and higher (2-3 m) in clayey sediments in the southeast. There have been no long-term trends in water levels apparent since 1977, except in BS1C where there has been a slight decline (Ventriss and Boyd, 1981), the reason for which is unknown.

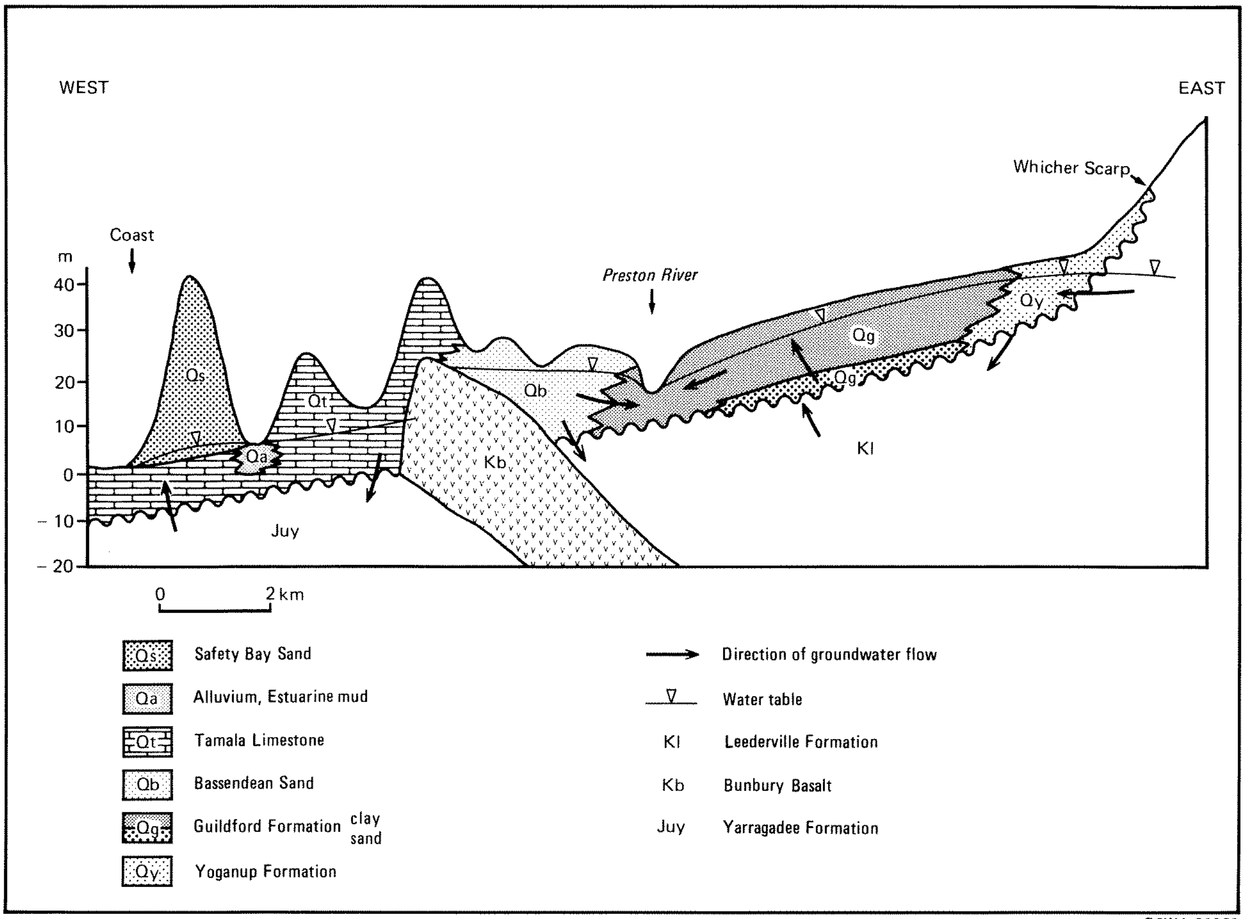


Figure 6. Diagrammatic section of the superficial formations illustrating directions of groundwater flow

Groundwater Quality: Groundwater tends to be fresh in areas of sand, and brackish to saline in areas of clay (Fig. 9). In the Yoganup Formation (BS23B) and nearby (BS14B), and in the Bassendean Sand (BS8B, BS12B), the salinity is less than 500 mg/L (Table 2). The salinity is less than 1 000 mg/L in the Tamala Limestone, but close to the coast in the Safety Bay Sand salinities are higher (Fig. 9), due in some cases to mixing with sea water.

The groundwater in the Guildford Formation exceeds 1 000 mg/L and ranges up to 5 000 mg/L between Dardanup and Burekup. The high salinities are in areas of heavy clay soils where the water table is shallow, surface drainage poor and where upward groundwater-discharge concentrates salts near the surface. Soil-salinity problems also occur in these areas of naturally high groundwater-salinity and these are made worse by irrigation, using water from Wellington Dam (George, 1980).

The major ions analysed in the groundwater are given in Table 2. Nitrate is present in significant amounts in BS7B and BS3B (40 mg/L, 22 mg/L) and in BS10B and BS17B (4 mg/L) and BS20B (3 mg/L); fluoride and boron concentrations do not exceed 0.6 mg/L and 0.7 mg/L respectively. The sulphate concentration in BS5B (280 mg/L) is anomalously high.

Development: Groundwater from the superficial formations is used only for on-farm domestic and stock supply and for irrigation of gardens in the urban areas of Bunbury, Australind, Eaton and Gelorup.

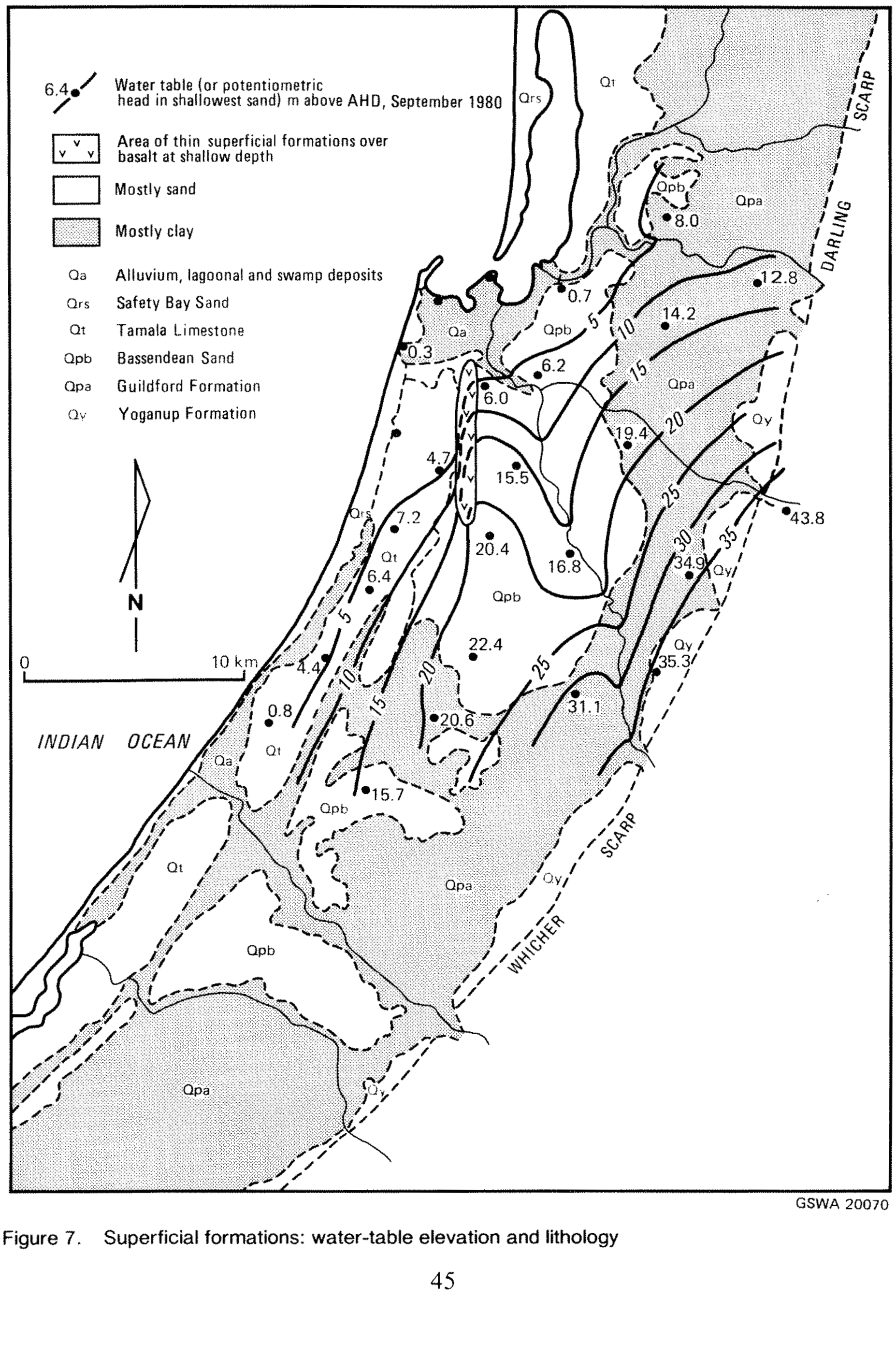


Figure 7. Superficial formations: water-table elevation and lithology

Leederville Formation

Groundwater Flow: A groundwater flow-system occurs in the Leederville Formation in the Dardanup Syncline, which is apparently partly connected with another flow-system in the Leederville Formation to the west of the Capel Anticline (Fig. 10).

Recharge to the eastern flow-system takes place by direct infiltration from rainfall and minor streams on the Blackwood Plateau. There is also some recharge through the Yoganup Formation and Bassendean Sand on the coastal plain where the hydraulic head is downwards (Fig. 8).

The Preston and Capel River valleys are not sources of recharge because they are incised below the regional potentiometric surface; flowing bores (e.g. QL8) may occur in these valleys.

Groundwater flow is northerly from the recharge areas on the Blackwood Plateau and is laterally restricted by the Darling Fault to the east and by the Capel Anticline to the west. The flow system is confined by the clays of the Guildford Formation on the coastal plain.

There are large vertical differences in hydraulic head within the formation. In the Blackwood Plateau the hydraulic head decreases with depth, and in QL8 there is a head difference of at least 30 m between the top and bottom of the formation. On the coastal plain the highest heads are in the middle of the

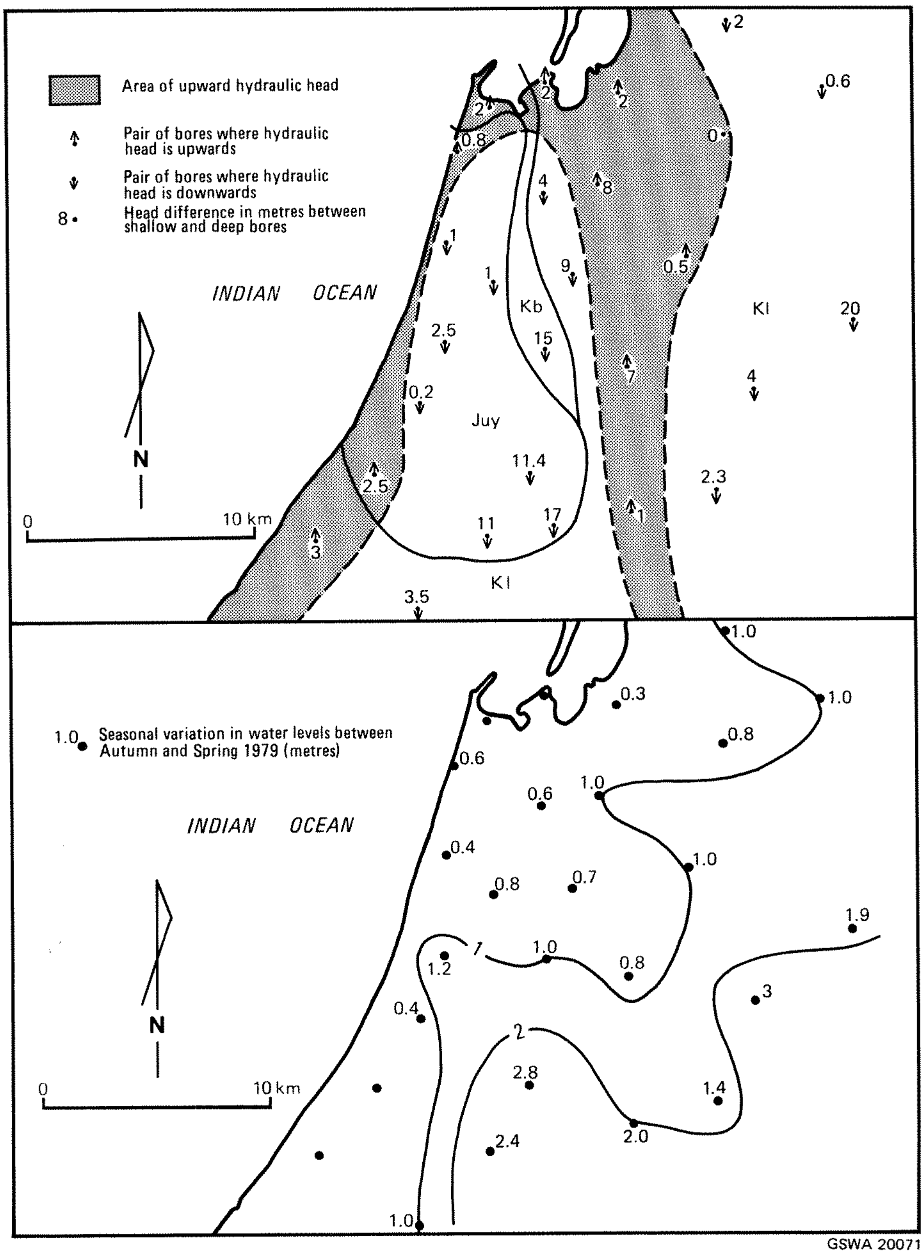


Figure 8. Superficial formations: hydraulic-head difference with the confined aquifers and seasonal variation in water table elevation

formation, with upward groundwater-flow to the superficial formations and downward groundwater-flow to the Yarragadee Formation—in which the hydraulic head (Fig. 11) is generally much lower. Because of the large, vertical, head differences within the formation, the water levels measured in the Bunbury Shallow bores are not strictly comparable and consequently the potentiometric-head map (Fig. 10) is only approximate.

Near Leschenault Inlet, groundwater flow is northwestward and groundwater discharge presumably takes place along the inlet above a body of intruding sea-water (Fig. 10). This is present in the upper part of the formation and overlies fresh water (Plate 1, Section AA).

The sea-water interface in the Leederville Formation occurs along the southeast shore of Leschenault Inlet (Fig. 10), and extends to depths of 45 m in the Bunbury Foods bore (Commander 1981), 100 m in the Eaton Recreation Reserve bore and to about 100 m in the Laporte 5 bore, but is west of the Australind town-water-supply bores.

West of the Capel Anticline the direction of groundwater flow is probably northwestwards (Fig. 10). Recharge takes place from the superficial formations east of the Bussell Highway where there are downward hydraulic-heads, and there is possibly some flow from the main flow-system in the Dardanup Syncline between the subcropping areas of Bunbury Basalt and Yarragadee Formation, shown on Figure 4.

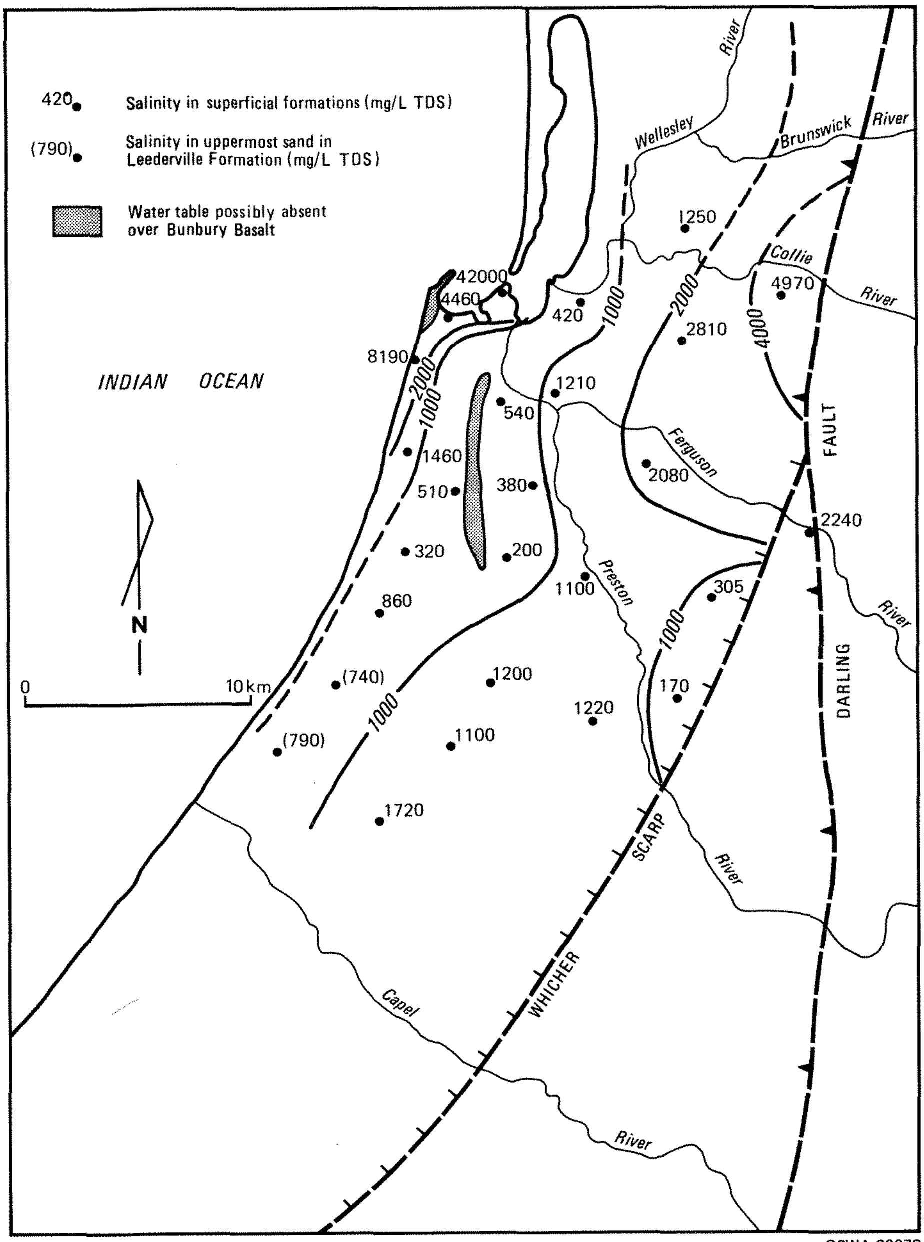


Figure 9. Superficial formations: salinity (mg/L TDS)

Discharge occurs into the coastal swamps through the superficial formations. A seawater-freshwater interface identified in the uppermost 60 m of the formation at Peppermint Grove provably extends along the coast (Fig. 10).

Throughflow: The throughflow (Q) in the Leederville Formation, across the width of the Dardanup Syncline, can be calculated from the equation:

$$Q = k\, b\, i\, l \text{ —(1)}$$

where k is the hydraulic conductivity of the sands
b is the average thickness of sand
i is the hydraulic gradient
l is the width of the section

using k = 15 m/day, derived from pumping tests (Table 3)

b = 100 m, based on lithological logs of bores and the cross sections (Fig. 3)

$i = 1.3 \times 10^{-3}$ (from Fig. 10) and

i = 15 000 m (along the 20 m potentiometric contour on Figure 10),

$Q = 15 \times 100 \times 1.3 \times 10^{-3} \times 15\,000$
$= 29\,250\ m^3/day$
$= 10.7 \times 10^6\ m^3$ per year
$\simeq 11 \times 10^6\ m^3$ per year.

There is insufficient data to calculate the throughflow west of the Capel Anticline.

Groundwater Quality: Groundwater salinity in the Leederville Formation is less than 1 000 mg/L, except close to the sea water interface.

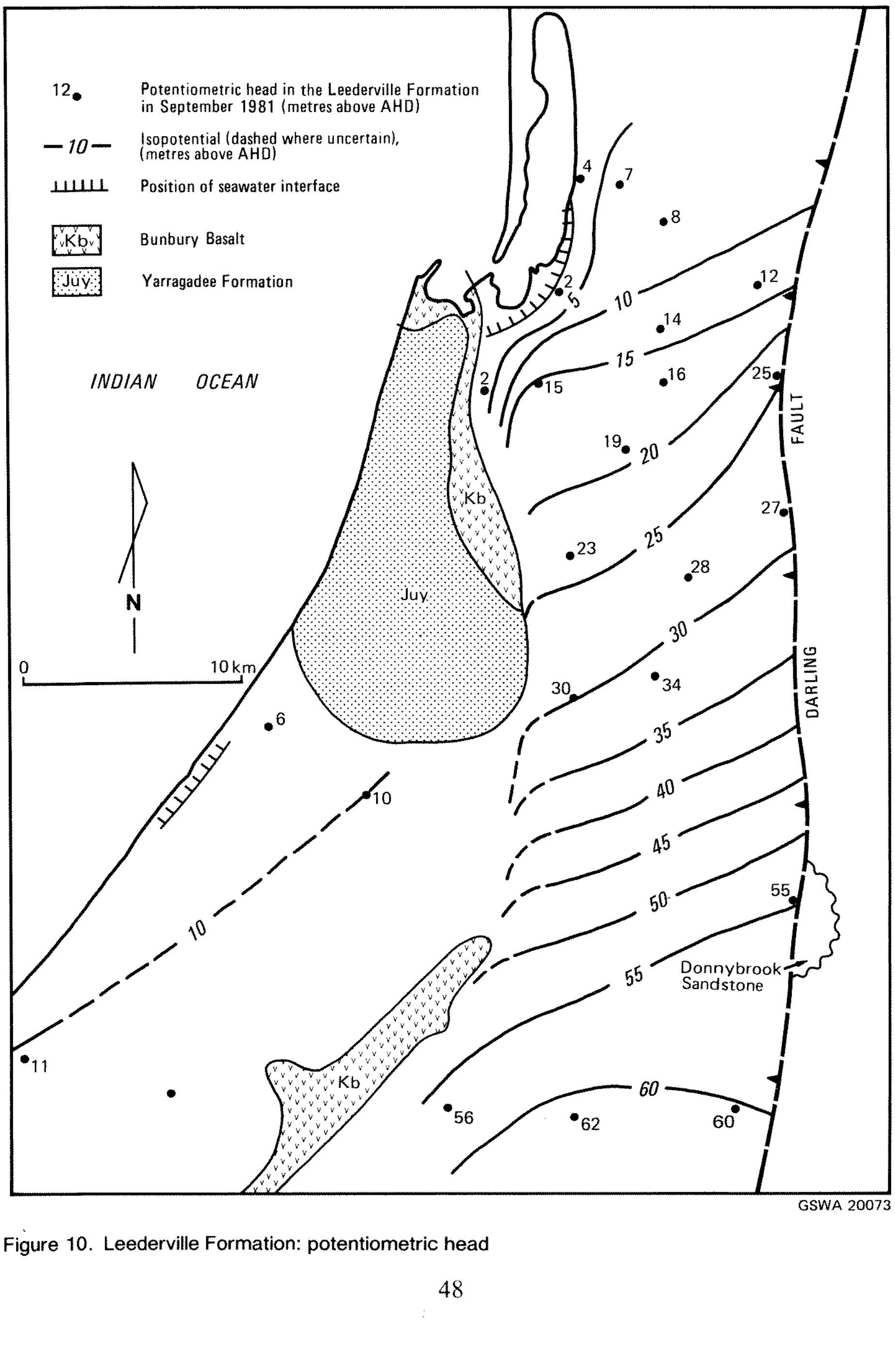


Figure 10. Leederville Formation: potentiometric head

In the Dardanup Syncline the lowest-salinity water (less than 300 mg/L in BS15 and BS16) occurs in the uppermost, sandy part of the formation which is preserved in the centre of the syncline. In the lower, more clayey part of the formation the salinity ranges up to 800 mg/L.

The salinity in BS4C of 2 131 mg/L is somewhat anomalous, but may be caused by local recharge of brackish water from the superficial formations.

Most groundwater in the Leederville Formation is of sodium-chloride type (Table 2) although in BS2A the proportion of bicarbonate exceeds that of chloride. Analyses for iron were not made because the samples were aerated, but the concentration of iron is low enough (less than 0.3 mg/L) in the Dardanup and Australind town-water-supply bores not to warrant treatment. Boron and fluoride concentrations do not exceed 0.3 mg/L.

Development: Groundwater from the Leederville Formation is used by the Australind, Dardanup and Donnybrook town-water supplies; by a few industrial consumers between Dardanup and Eaton; and by farms for domestic and stock water especially in areas where the groundwater in the overlying superficial formations is brackish or saline.

The estimated abstraction is less than 1 x $10^6 m^3$ per year, about one tenth of the estimated throughflow, consequently there is potential for further development. In the Eaton-Australind area there may be future problems with inland movement

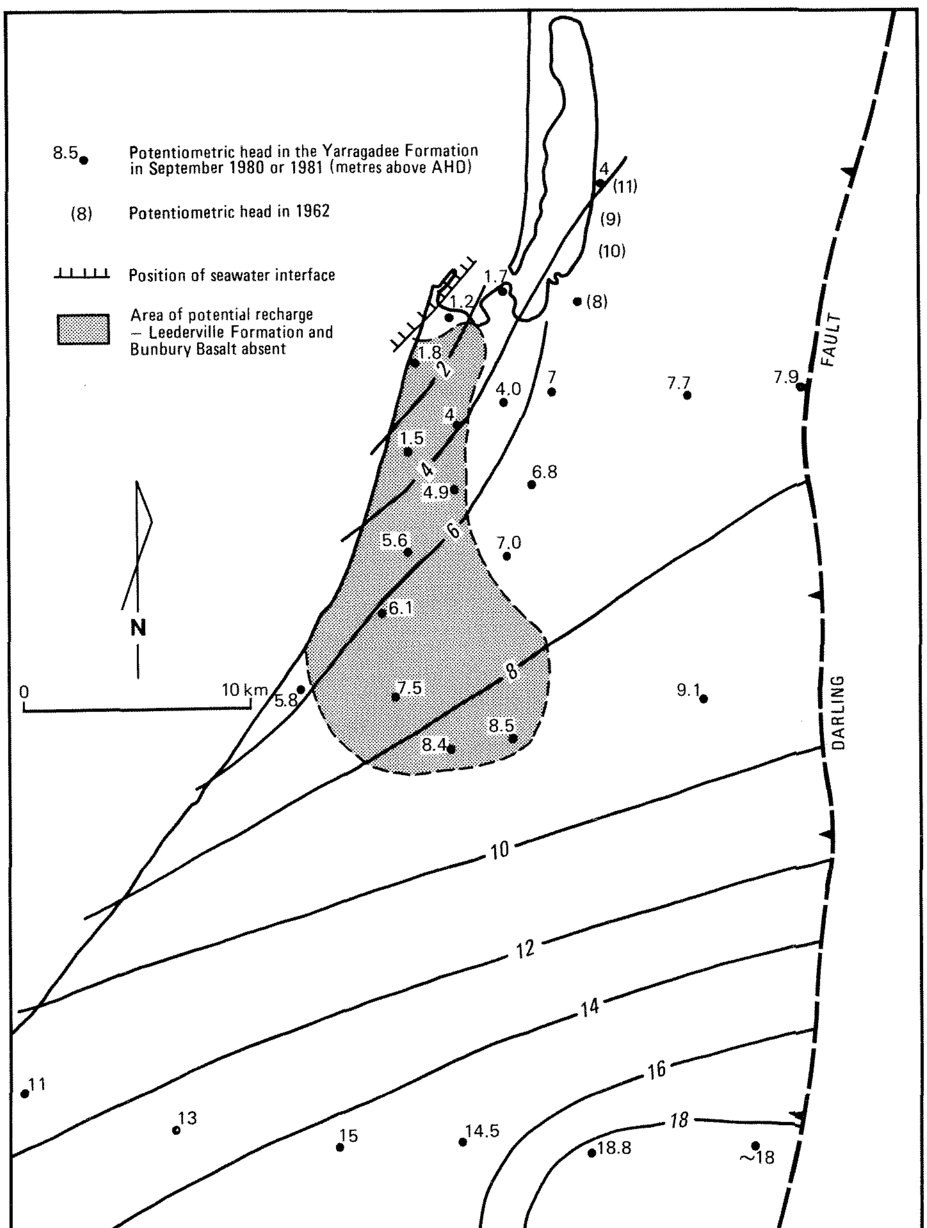


Figure 11. Yarragadee Formation: potentiometric head

of the sea water interface. At BS2A the water level has been progressively lowered by nearby groundwater abstraction and is now below sea-level for several months each year, indicating that there is potential for landward movement of the sea water interface.

Yarragadee Formation and Cockleshell Gully Formation

Groundwater Flow: A major fresh-groundwater flow-system occurs in the Yarragadee Formation and extends throughout the Perth Basin in the Bunbury area. The base of the flow system is an interface with saline or hypersaline groundwater and this often coincides with the contact between the sands of the Yarragadee Formation and the interbedded sands and shales of the Cockleshell Gully Formation.

The interface is at a depth of about 1 000 m in the Quindalup Line bores, within the Yarragadee Formation (Wharton, 1981); at a depth of about 800 m in the Boyanup Line bores, at the contact of the Yarragadee and Cockleshell Gully Formations (Smith, pers. comm.); and at a depth of 600 m in the Picton Line bores at the contact of the Yarragadee and Cockleshell Gully Formations, except in PL2 where the formation contact is shallower and the flow system also occurs in the upper part of the Cockleshell Gully Formation.

Most of the groundwater flow is in the lower, sandy part of the formation because the upper part, which is preserved close to the Darling Fault (Smith, pers. comm.; Wharton 1980, 1981) is predominantly clayey.

The Bunbury shallow bores which encountered the Yarragadee Formation (Fig. 11), penetrated only a small proportion of the total thickness of the formation. There are only small vertical variations in potentiometric head so that a relatively reliable isopotential map can be drawn. The isopotential map shows that the groundwater flow is from south to north, and to the northwest close to Bunbury. The main recharge to the aquifer is inferred to take place on the Blackwood Plateau south of the Quindalup Line. Recharge also takes place from the Leederville Formation and from the superficial formations on the coastal plain.

In the shaley upper part of the Yarragadee Formation in PL4 and QL9 there are large vertical hydraulic gradients. The groundwater salinity in this part of the Yarragadee Formation is similar to that in the overlying Leederville Formation, and groundwater flow is presumed to occur between the two formations.

The potentiometric head in the Laporte (Australind) and Eaton bores in 1962/3 was 9 to 11 m above sea level (Passmore 1962, Emmenegger, 1963a). These heads are significantly higher than those presently recorded in the Picton Line bores (Fig. 11), suggesting either that there has been a decline in head over a sufficiently large area to affect the Picton Line bores, or that there is a local source of recharge from the north, presumably by leakage through the Leederville Formation.

The natural seasonal variation in water level in the aquifer is about 0.6 m, but near to Bunbury the annual change in water level is increased due to abstraction for Bunbury water supply (Commander, 1981). Hydrographs (Ventriss and Boyd, 1981) show that in bores affected by pumping the water levels are lowest in February, whereas in bores elsewhere the levels are lowest in March or April.

Discharge from the Yarragadee Formation occurs via the superficial formations into the ocean southwest of Bunbury, where the confining Leederville Formation and Bunbury Basalt are absent.

The sea-water interface is probably a complex series of sea-water wedges and is mostly offshore, presumably parallel to the isopotentials. The interface has been encountered by drilling, only in the Symmons Street bore near Casuarina Point, where saline water occurs below the Bunbury Basalt (Rowston, 1969). The interface here may have been drawn inland by the reduction in potentiometric head in the upper 50 metres of the Yarragadee Formation, caused by pumping for Bunbury water-supply.

Throughflow: The throughflow (Q) in the Yarragadee Formation across the 10 m potentiometric-head contour (Fig. 11) can be estimated from equation (1). Using a hydraulic conductivity (k) of 20 m/day (derived from pumping tests at BS10 and from BWB bores Table 3), an average thickness (b) of 600 m of sand in the formation, (from information along the Boyanup Line), and a hydraulic gradient (i) of 0.4 x 10^{-3} between PL2 and the 14 m potentiometric contour, the throughflow across the 38 km length (l) of the 10 m potentiometric-head contour on Figure 11 is—

$Q = 20 \times 600 \times 0.4 \times 10^{-3} \times 38\,000 \simeq$
$180\,000\ m^3/d \simeq 66 \times 10^6\ m^3$ per year.

Groundwater Quality: The groundwater salinity of the flow system in the Yarragadee Formation and Cockleshell Gully Formation is mostly less than 500 mg/L. It is lowest in the Quindalup Line bores (less than 200 mg/L), and increases northwards to 300-360 mg/L in the Picton Line bores (Wharton 1980, 1981).

At the base of the flow system there is a rapid salinity increase to 10 000 mg/L or more, within 100 m. (Smith, pers. comm.; Wharton 1980, 1981). A maximum salinity of 51 700 mg/L occurred about 400 m below the interface in PL1 (Wharton, 1980).

In the Laporte bores at Australind (Passmore, 1962) the salinity ranges up to 1 133 mg/L, which may be due to local brackish recharge from the Leederville Formation.

The major ionic constituents analysed in the Yarragadee Formation groundwater, from the Bunbury shallow bores, are sodium chloride or sodium bicarbonate (Table 2). Relatively high concentrations of iron are a feature of groundwater in Bunbury where concentrations of as much as 6.6 mg/L occur (Commander, 1981) and treatment is usually necessary for town-water-supply use. Manganese concentrations of 4.3 mg/L and 8.0 mg/L have been measured from two BWB bores (Commander, 1981), but are small elswhere. Boron and fluoride concentrations are usually less than 0.2 mg/L, except in BS21A (0.5 mg/L) and BS10A (0.6 mg/L).

Development: The Yarragadee Formation is used for town-water supply, industry, and mineral-sand processing. Estimates of usage are given in Table 5.

Groundwater abstraction in Bunbury has caused a lowering of the potentiometric head in the upper part of the aquifer within the city, and a steepening of the hydraulic gradient to the east. The amount by which the potentiometric surface has been drawn down since abstraction began is unknown, but records of SEC bores drilled in 1955 show that the potentiometric head was 3 to 4 metres above AHD, whereas in spring 1980 the head was less than two metres above AHD, suggesting that there has been a decline in head of only one to two metres in 25 years. The seasonal pumping in Bunbury has caused a variation in water levels of as much as 5 m in observation bores close to production bores (Commander 1981, Ventriss and Boyd, 1981).

TABLE 5
ESTIMATED GROUNDWATER ABSTRACTION FROM THE YARRAGADEE FORMATION

Consumer	Annual abstraction (x 10^6 m^3)
Town Supply (metered)	
Bunbury (Town supply)	7
(Parks and gardens)	1
Australind/Eaton	0.6
Boyanup	0.14
Capel	0.13
Industry (estimated from licensed bore capacity)	
Laporte (Australind)	3
Cable 1956 Ltd (Koombana Bay, Stratham)	1.4
State Energy Commission (Bunbury)	0.3
Australian Minerals Consolidated (Capel South)	2.5
WSL Group (Capel North, Yoganup)	2.5
TOTAL	18.57

There has been a substantial lowering of potentiometric head in the Eaton-Australind area since pumping began in the early 1960s. The potentiometric head in the uppermost part of the Yarragadee Formation, in PWD Eaton 3 bore, had declined from 8.5 m (AHD) in 1963 to a mean close to sea-level (Ventriss and Boyd, 1981), due to abstraction from the Laporte borefield.

In Bunbury there are seasonal fluctuations in the salinity of BWB bores close to the ocean due to landward movement of the salt-water interface (Commander, 1981).

CONCLUSIONS

The Bunbury shallow-drilling programme has refined the known extent and structure of the Bunbury Basalt and of the two major aquifers in the area, the Yarragadee and Leederville Formations.

The bores provide a grid which defines the potentiometric surface of the two major aquifers and has enabled the calculation of throughflow. It is estimated that annual throughflow is 66 x 10^6 m^3 in the Yarragadee Formation and 11 x 10^6 m^3 in the Leederville Formation.

Monitoring of the bores has provided data on the effects of groundwater abstraction in and near Bunbury, and will assist the future management of the aquifers.

REFERENCES

Barnes, R. G., 1970, Report on the geology and deeper groundwater prospects in the Bunbury district of the South Perth Basin. West. Australia Geol. Survey Hydrogeology Rept 821 (unpublished).

——— 1974, The geology and hydrology of the Laporte effluent disposal area, west of Leschenault Inlet: West. Australia Geol. Survey Hydrogeology Rept 1174 (unpublished).

Baxter, J. L., 1977, Heavy mineral sand deposits of Western Australia: West. Australia Geol. Survey Mineral Resources Bull. 10, p.148.

Boyd, D. W., 1979, Bunbury groundwater management review: West Australia Public Works Dept, Water Resources Technical Rept 85 (unpublished).

Bureau of Mineral Resources, 1960, Busselton-Collie W.A. 1:253 440 sheet: Total magnetic intensity map measured by airborne magnetometer.

Burgess, I. R., 1978, Geology and geochemistry of the Cretaceous Bunbury tholeiite suite, Perth Basin, Western Australia: Univ. West. Australia Hons. Thesis (unpublished).

Commander, D. P., 1976, Bunbury groundwater investigation—preliminary report to December 1975; West. Australia Geol. Survey Hydrogeology Rept 1345 (unpublished).

——— 1981, The geology and hydrogeology of Bunbury: West. Australia Geol. Survey Hydrogeology Rept 2327 (unpublished).

Emmenegger, C., 1963a, Report on Laporte No. 5 water bore Australind. W.A.: West. Australia Geol. Survey Rec. 1963/1 (restricted).

———1963b, Report on Eaton No 1. bore: West. Australia Geol. Survey Rec. 1963/3.

———1963c, Report on Capel town bore No. 1: West. Australia Geol. Survey Rec. 1963/15.

George, P. R. 1980, Soil salinity in the South West irrigation area; proceedings of seminar on irrigation of farms in the south west of Western Australia: West. Australia Agriculture Dept Bunbury Sept. 1980.

Harley, A. S., 1973, Recommendations for exploratory drilling east of Bunbury. West. Australia Geol. Survey Hydrogeology Rept 1147 (unpublished).

Leach, R. E. J., 1977, Extension of the Bunbury groundwater investigation: West. Australia Geol. Survey Hydrogeology Rept 1470 (unpublished).

Low, G. H., 1971, Definition of two Quaternary formations in the Perth Basin: West. Australia Geol. Survey Ann. Rept 1970, p.33-34.

Lowry, D. C., 1965, Geology of the southern Perth Basin: West. Australia Geol. Survey Rec. 1965/17.

McArthur, W. M., and Bettenay, E., 1974, The development and distribution of the soils of the Swan Coastal Plain: Australia CSIRO Soil Pub. No. 16, 2nd Edition.

Maitland, A. G., 1898, Artesian Water—Bunbury: West. Australia Geol. Survey Ann. Progress Rept 1897, p.30.

——1913, The artesian water resources of Western Australia: Appendix M in Interstate conference on Artesian water Report 1912, Sydney, Government Printer.

Passmore, J. R., 1962, Report on Laporte Nos 1, 2, 3 and 4 water bores, Australind, W.A.: West. Australia Geol. Survey Rec. 1962/12.

Playford, P. E., and Low, G. H., 1972, Definitions of some new and revised rock units in the Perth Basin: West. Australia Geol. Survey Ann. Rept 1971, p.44-46.

Playford, P. E., Cockbain, A. E., and Low, G. H., 1976, Geology of the Perth Basin, Western Australia: West. Australia Geol. Survey Bull. 124.

Probert, D. H., 1968, Groundwater in the Busselton area, progress report on exploratory drilling. West. Australia Geol. Survey Ann. Rept 1967, p.12-17.

Rowston, D. L., 1969, Bunbury Symmons St. Bore: West. Australia Geol. Survey Well-logging Rept 1969/6 (unpublished).

Trendall, A. F., 1962, Plagioclase phenocrysts in a basalt from Boyanup, Western Australia: West. Australia Geol. Survey Rec. 1962/21.

Ventriss, H. B., and Boyd, D. W., 1981, Bunbury groundwater system management review 1981. West. Australian Public Works Dept Water Resour. Branch Rept No. WRB 1.

Wharton, P. H., 1980, The geology and hydrogeology of the Picton borehole line: West. Australia Geol. Survey Ann. Rept 1979, p.14-19.

——1981, The geology and hydrogeology of the Quindalup borehole line: West. Australia Geol. Survey Ann. Rept 1980, p.27-35.

Whincup, P., 1968, Artesian basin—Bunbury area selection of sites for observation of water levels: West. Australia Geol. Survey Hydrogeology Rept 620 (unpublished).

Wilde, S. A. and Walker, I. W., 1979, Explanatory notes on the Collie 1:250 000 Geological sheet, Western Australia: West. Australia Geol. Survey Rec. 1979/11.