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Hydrogeology of the coastal plain between Cervantes and Leeman, Perth Basin

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Cover Photograph:
Lake Indoon, 12 km southwest of Eneabba

HYDROGEOLOGY OF THE COASTAL PLAIN BETWEEN CERVANTES AND LEEMAN, PERTH BASIN

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Abstract

The hydrogeology of the coastal plain between Cervantes and Leeman in the northern Perth Basin has been investigated by drilling 33 bores at 17 sites on a 7 km grid. The bores were drilled between March and May 1993, with the exception of bores 8A and 8B which were drilled in October 1990, and they range in depth from 20.0 to 105.5 m with an aggregate of 2142.6 m. Results from drilling have shown that the superficial formations comprise a number of formations of Tertiary–Quaternary age that form a stratigraphically complex sequence up to 120 m thick and which unconformably overlie the Mesozoic formations. Over most of the area, the superficial formations are underlain by the Lesueur Sandstone, Eneabba Formation, Cattamarra Coal Measures and Yarragadee Formation. In the investigation area these units have generally faulted contacts.

Groundwater is contained in an unconfined aquifer system in the superficial formations and an unconfined to confined aquifer system in the Mesozoic formations. The saturated thickness of the unconfined aquifer varies significantly across the coastal plain and reaches a maximum of about 35 m southwest of Eneabba. The unconfined aquifer is recharged directly from rainfall and to a lesser extent by discharge from the underlying Mesozoic formations. Groundwater from both aquifer systems is discharged to the ocean above a saltwater interface, which in places extends as much as 5 km inland.

Groundwater in the superficial formations is fresh to saline (800–33 900 mg/L TDS) whereas the Lesueur Sandstone contains large volumes of fresh to slightly brackish groundwater (500–1850 mg/L TDS). The Yarragadee Formation forms a large aquifer containing fresh groundwater in the Eneabba area. Groundwater with a salinity of less than 1000 mg/L TDS is locally present in the Eneabba Formation, whereas the relatively thinner sandstone beds in the Cattamarra Coal Measures contain only brackish to saline groundwater. The estimated groundwater storage in the superficial formations is 5.6 x 10^9 m^3 and the estimated total throughflow is 82.8 x 10^6 m^3/year.

KEYWORDS: Perth Basin, Swan Coastal Plain, hydrogeology, geology, groundwater, stratigraphy.

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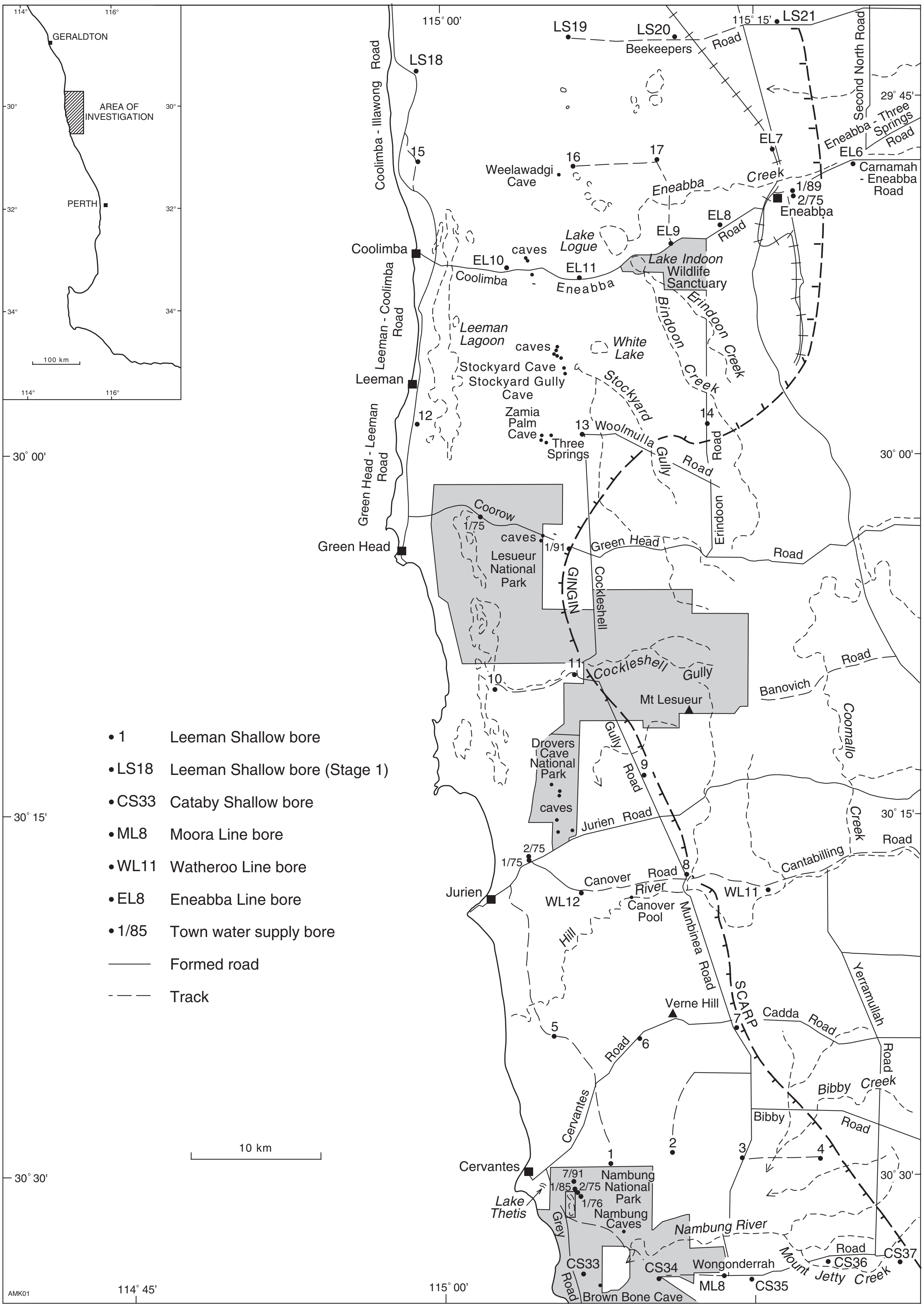

Figure 1. Bore location

Introduction

Location

The investigation area extends over 1685 km^2 of the Swan Coastal Plain between Cervantes and Leeman. The project was named the Leeman shallow-drilling project after the coastal town of Leeman, approximately 240 km north-northwest of Perth (Figure 1).

Purpose and scope

The Leeman shallow-drilling project (Kern, 1993a) was originally proposed as a northward extension of the Cataby Project, which was completed in 1987. The drilling program commenced in 1990 in the northern half of the proposed area, between about 20 km north of Leeman and Dongara (sites LS18–34), and at one site (LS8) in the south in 1990 (Nidagal, 1995), but work ceased owing to the closure of the Mines Department Drilling Branch. Drilling was recommenced in the southern half of the original project area, between Cervantes and about 20 km north of Leeman, in 1993. This report includes the results from sites LS1–17.

The investigation was carried out by the Geological Survey of Western Australia (GSWA) as part of a long-term program to evaluate the groundwater resources of the Perth Basin. The objectives were:

- to investigate the hydrogeology of the Swan Coastal Plain in the northern Perth Basin,
- to assess the groundwater resources of the area, and
- to establish a network of groundwater observation bores for long-term monitoring.

Climate and landuse

The region has a Mediterranean climate characterised by hot, dry summers and mild, wet winters. The average annual rainfall decreases eastward from 681 mm at Leeman on the coast to 511 mm at Eneabba about 30 km inland. Most of the rain falls during the winter months between April and September. The average annual evaporation is about 2200 mm at Leeman and rainfall exceeds evaporation only during the winter months.

The major industries in the project area are heavy-mineral sand mining in the Eneabba area, production of gas and condensate from the Woodada gasfield and offshore rock-lobster fishing. Agriculture consists mainly of sheep and cattle grazing and cereal growing, and large areas have been cleared for this purpose east of outcrops of the coastal limestone (Tamala Limestone). Irrigation of lucerne and clover is also carried out near White Lake, southwest of Eneabba. Uncleared land along the coast and in the central area is mostly unalienated crown land covered by native vegetation and includes the Lesueur and Drovers Cave National Parks (Figure 1). Native plants flower throughout the year and attract a large number of tourists and apiarists, as well as a small number of commercial wildflower harvesters.

Eneabba supports the nearby mineral-sand operations and local farming communities. The coastal towns of Cervantes, Jurien, Green Head and Leeman are centres for the rock-lobster industry, and also support fishing and tourism. Other settlements in the area include groups of squatters and fishing shacks along the coast.

The Brand Highway crosses the northeast of the project area and provides access south to Perth and north to Geraldton. Sealed and unsealed roads provide access to the small coastal towns of Cervantes, Jurien, Green Head and Leeman.

Physiography

Landforms

The investigation area covers the Swan Coastal Plain, which is a low-lying area covered by Quaternary coastal sediments and alluvium and bounded to the east by the Gingin Scarp. The scarp was formed by marine erosion and separates the coastal plain from the Arrowsmith Region to the east. The Swan Coastal Plain consists of a series of distinct landforms, roughly parallel to the coast: the Quindalup Dune System, the Spearwood Dune System, the Bassendean Dunes, and the Eneabba Plain (Figure 2).

The Quindalup Dune System is a narrow Holocene coastal-dune zone composed of the Safety Bay Sand, which forms both stabilised and mobile dunes up to 28 m high. These overlap the Spearwood Dune System, which consists

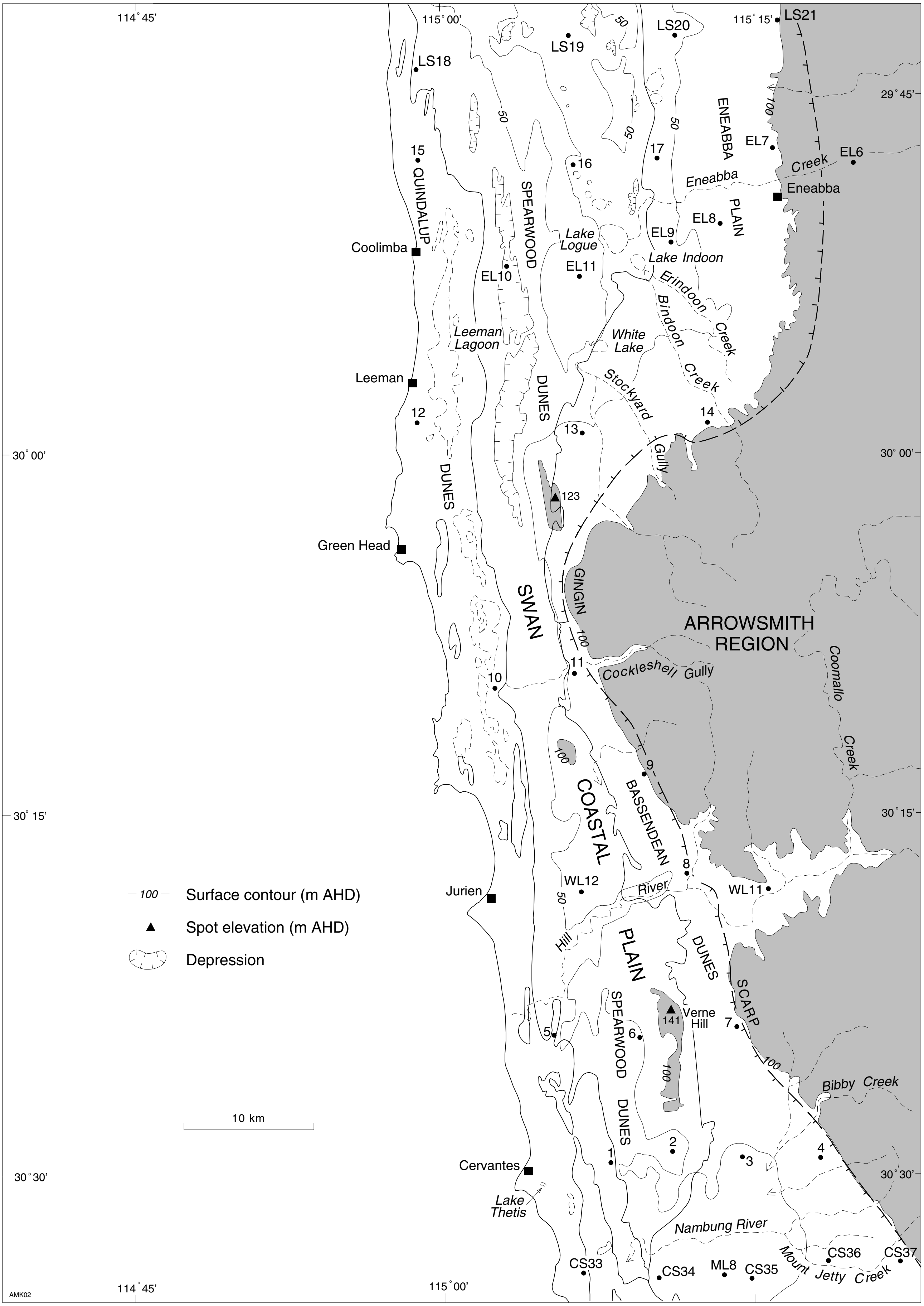

Figure 2. Physiography

largely of lithified Pleistocene eolianite with leached quartz sand (Tamala Limestone). The Tamala Limestone commonly forms low hills that follow the old dune topography, but is exposed in low-lying cliffs along some sections of the coast. The dune system extends up to 19 km inland in the Coolimba–Eneabba area. There are locally well-developed cave systems in the Spearwood Dune System. The Bassendean Dunes represent a belt of coastal dunes and associated shoreline deposit in a low-lying area between the Spearwood Dune System and the Gingin Scarp south of Cockleshell Gully. South of Hill River the Bassendean Dunes include the Munbinea Shoreline, which contains high concentrations of heavy-mineral sands. The Eneabba Plain consists of a series of shoreline, lagoon, and dune deposits, which locally have high concentrations of heavy minerals in a low-lying area between the Spearwood Dune System and the north re-entrant of the Gingin Scarp.

Drainage

The area is drained by watercourses originating in the Arrowsmith Region. All of these watercourses, with the exception of the Hill River, terminate in swamps and lakes in interdunal depressions in the western half of the Swan Coastal Plain. When the lakes are full, water overflows into the cave systems. Drilling results in the northern area indicate that the freshwater lakes west of Eneabba are perched. Salt lakes lie between the Quindalup and Spearwood Dune Systems near the coastal town of Leeman.

Previous work

The superficial formations of the coastal plain were mapped by Lowry (1974) between 1968 and 1969, and the regional geology has been described by Playford et al. (1976). The investigation area was remapped at the scale of 1:100 000 by Mory (1994a, b) in 1989.

The earliest reports on groundwater are from exploratory drilling for water at Jurien by the Geological Survey of Western Australia (Berliat and Morgan, 1962; Milbourne, 1967). Subsequently the Watheroo – Jurien Bay Line of exploratory water bores, which includes bores WL11 and WL12, was drilled between 1971 and 1972 (Harley, 1974, 1975). Following a farm-bore census of the Eneabba area, drilling of the Eneabba Line of exploratory water bores (EL7-11) to depths of 797 m was carried out between 1972 and 1974 (Commander, 1978). The hydrogeology in the area north of Hill River is described in detail in an unpublished thesis by Commander (1981). Between 1972 and 1994 the Public Works Department and the Water Authority of Western Australia produced unpublished reports on the town water supplies of Cervantes, Jurien, Leeman – Green Head and Eneabba. An assessment of groundwater abstraction by mineral sand companies at Eneabba has been prepared by Commander (1980). Following the first drilling results from the second stage of the Leeman shallow-drilling project a report on the Cervantes town water supply was prepared in 1993 (Kern, 1993b) and includes a description of the hydrogeology between Cervantes and Jurien. Brief descriptions of the hydrogeology are given in the Hill River – Green Head and Arrowsmith – Beagle Island 1:100 000 geological maps series explanatory notes (Commander 1994a, b).

The first stage of the Leeman shallow-drilling project was carried out between Eneabba and Dongara (Nidagal, 1991, 1994). The hydrogeology of the coastal plain south of Cervantes is described by Kern (1993a, 1995) based on the results from exploratory drilling of the Cataby shallow-drilling project. Bore completion reports for the Leeman shallow-drilling project were completed in 1994 (Kern, 1994).

Table 1. Bore data

Bore	AMG Zone 50 Easting	AMG Zone 50 Northing	Construction Com-menced (m AHD)	Construction Comp-leted (m AHD)	Elevation Surface (m)	Elevation Top of casing cap (m bns)	Total depth	Screened interval	Formation screened	Head *(a)* (m AHD)	Salinity (mg/L TDS)	Base *(b)* (m AHD)	Status of bore
LS1A	320 900	6 625 250	24.04.93	30.04.93			86.8	77.0 – 83.0	Lesueur S			-6	abandoned
LS1B	320 900	6 625 250	01.05.93	01.05.93	33.740	34.742	43.0	37.3 – 43.3	Tamala L/ Lesueur S	0.08	1 240	-6	observation
LS1C	320 900	6 625 250	19.05.93	20.05.93	33.743	34.711	84.0	77.0 – 83.0	Lesueur S	0.35	910	-6	observation
LS2A	325 600	6 626 100	10.05.93	17.05.93	25.965	27.409	80.9	64.3 – 70.3	Lesueur S	19.28	1 850	15	observation
LS2B	325 600	6 626 100	17.05.93	18.05.93	25.966	27.239	22.0	16.0 – 22.0	Lesueur S	17.28	1 300	15	observation
LS3A	331 100	6 625 700	18.05.93	19.05.93	47.355	48.323	100.0	81.0 – 87.0	Cattamarra CM	47.94	1 500	40	observation
LS3B	331 100	6 625 700	20.05.93	20.05.93	47.357	48.227	30.0	24.0 – 30.0	Cattamarra CM	46.13	8 270	40	observation
LS4A	337 000	6 625 800	21.05.93	25.05.93	73.254	74.371	100.0	86.0 – 92.0	Cattamarra CM	73.72	1 600	65	observation
LS4B	337 000	6 625 800	25.05.93	25.05.93	73.247	74.224	20.0	14.0 – 20.0	?Cadda F	72.78	3 690	65	observation
LS5A	316 400	6 635 000	15.04.93	21.04.93	33.576	34.756	99.5	84.0 – 90.0	Lesueur S	0.88	2 100	-15	obs/damaged
LS5B	316 400	6 635 000	22.04.93	22.04.93	33.644	34.860	44.7	38.7 – 44.7	Tamala L	0.90	800	-15	observation
LS6A	322 800	6 634 900	03.05.93	07.05.93	33.402	34.627	99.4	93.1 – 99.1	Lesueur S	14.52	780	8	observation
LS6B	322 800	6 634 900	07.05.93	07.05.93	33.425	34.508	34.5	28.0 – 34.0	Lesueur S	14.65	670	8	observation *(c)*
LS7A	330 100	6 635 900	13.05.93	17.05.93	85.656	86.588	100.0	78.0 – 84.0	?Eneabba F	78.59	1 010	79	observation
LS7B	330 100	6 635 900	17.05.93	17.05.93	85.655	86.672	37.0	31.0 – 37.0	?Eneabba F	80.98	1 300	79	observation
LS8A	326 200	6 647 200	2.10.90	4.10.90	57.580	58.356 *(d)*	100.0	75.0 – 81.0	Cattamarra CM	51.78	5 630	44	observation
LS8B	326 200	6 647 200	4.10.90	4.10.90	57.645	58.420 *(d)*	37.0	31.0 – 37.0	Cattamarra CM	51.67	5 210	44	observation
LS9A	322 800	6 655 000	11.05.93	12.05.93	91.598	92.660	100.0	90.0 – 96.0	Lesueur S	80.22	670	77	observation
LS9B	322 800	6 655 000	12.05.93	12.05.93	91.691	92.610	39.0	33.0 – 39.0	Lesueur S	80.68	960	77	observation
LS10A	311 400	6 661 700	13.04.93	13.04.93	3.269	4.192	27.5	11.4 – 17.4	Tamala L	0.59	3 970	-14	observation
LS11A	317 700	6 662 600	05.05.93	07.05.93	77.957	78.394	94.0	76.0 – 88.0	Lesueur S	74.26	490	69	observation
LS11B	317 700	6 662 600	10.05.93	10.05.93	77.932	79.035	46.0	40.0 – 46.0	Lesueur S	62.34	1 100	69	observation
LS12A	304 900	6 681 500	03.04.93	06.04.93	0.679	1.695	42.4	15.8 – 21.8	Tamala L	-0.14	33 900	-22	observation
LS13A	318 000	6 681 500	27.04.93	29.04.93	55.057	55.867	100.0	94.0 –100.0	Eneabba F	46.35	1 360	22	observation
LS13B	318 000	6 681 500	29.04.93	29.04.93	55.057	56.403	51.0	43.0 – 51.0	Eneabba F	45.97	2 900	22	observation
LS14A	327 200	6 682 300	30.04.93	05.05.93	93.230	94.483	97.0	89.0 – 95.0	Eneabba F	73.16	1 040	78	observation
LS14B	327 200	6 682 300	05.05.93	05.05.93	93.231	94.448	36.0	30.0 – 36.0	Eneabba F	73.87	540	78	observation
LS15A	304 700	6 702 200	21.05.93	25.05.93	2.334	3.306	105.5	94.0 –100.0	Eneabba F	-0.07	26 600	-21	observation
LS15B	304 700	6 702 200	22.04.93	23.04.93	2.524	3.319	24.0	16.0 – 24.0	Tamala L	-0.26	33 400	-21	observation
LS16A	316 700	6 702 000	24.03.93	31.03.93	36.548	37.651	99.4	71.7 – 77.7	Cadda F	15.54	1 310	13	observation
LS16B	316.700	6 702 000	30.03.93	31.03.93	36.588	37.992	23.0	17.0 – 23.0	Tamala L	13.42	-	13	abandone
LS17A	323 200	6 702 600	19.04.93	20.04.93	46.249	47.218	100.0	74.0 – 80.0	?Cadda F	26.38	1 900	23	observation
LS17B	323 200	6 702 600	20.04.93	21.04.93	46.264	47.243	39.0	33.0 – 39.0	?Cadda F	27.67	2 290	23	observation

(a) Potentiometric head: May 1993
(b) Base of superficial formations
(c) Slightly damaged near top
(d) Top of casing

Investigation program

Drilling and bore construction

The second stage of the Leeman Shallow drilling program was commenced in March 1993. The investigation bores were drilled simultaneously by Drillcorp Ltd with a VK 600 rig using wireline coring to penetrate the cavernous Tamala Limestone in the coastal area, and elsewhere by Yellowstone Holdings with a Mayhew 1400 rig using mud-rotary techniques. This report also includes the results of bores 8A and 8B, which were drilled by the Mines Department Drilling Branch in 1990. A network of 33 bores with an aggregate depth of 2142.6 m was drilled at 17 sites located on an approximately 7 km-square grid. Information from the Watheroo and Eneabba Lines has also been used for hydrogeological interpretation (Harley, 1975; Commander, 1978).

At most sites, drilling consisted of a deep bore (to a depth of about 100 m) to monitor the deep, unconfined to confined aquifer and a shallow bore to monitor the watertable. The depth drilled ranged from 20.0 to 105.5 m and the casing diameter from 50 to 80 mm. The deep bore was drilled first to about 100 m to fully penetrate the superficial formations and to intersect the underlying Mesozoic formations. Depending on the depth to the watertable and the stratigraphy, a shallow bore was subsequently drilled to about 10 m below the watertable. Where there is clay at the watertable, the bore was deepened until the underlying sand was intersected.

The bores were completed as monitoring bores with either 50, 55 or 80 mm diameter PVC casing and a 6 m length of stainless-steel or PVC screen at the monitoring interval. The annulus between the borehole and the casing was packed with gravel and sand. A protective steel casing about 1 m long and 100 mm diameter, fitted with a locking cap, was cemented at the surface.

Table 1 provides a summary of bore data and construction specifications, and detailed geological logs are given in Kern (1994).

Sampling and logging

Continuous cores were obtained with the wireline-drilling technique used by the VK 600 rig, and sludge samples were collected only when core recovery was uncertain. The wireline-drilling technique provided good core recovery, commonly varying between 30 and 50% for unconsolidated fine to very fine sand to more than 80% from Cainozoic limestone, and from well-consolidated Mesozoic sandstone and siltstone. In the bores drilled by the Mayhew 1400 rig, sludge samples were taken at 3 m intervals and at any changes in lithology.

All the samples were lithologically logged and are stored in the GSWA core library. The Mesozoic sediments were sampled for palynological analysis (Backhouse, J., unpublished reports *listed in* Kern, 1994). Gamma-ray logs were run in all the deep bores either in the open hole or through the drill pipes, depending on the stability of the holes. Electrical logs were run in the deep holes drilled by conventional mud-rotary in order to evaluate the groundwater salinity prior to the installation of PVC casing. In addition, temperature loging was carried out in a few boreholes.

Water sampling

On completion of casing and gravel packing, the bores were developed and sampled by airlifting, and the yield estimated. Airlifted water samples collected from each bore were analysed by the Chemistry Centre of Western Australia (Table 2)

Levelling and monitoring

The natural surface and top of casing of each bore was levelled to the Australian Height Datum (AHD) by the Department of Minerals and Energy Surveys and Mapping Division. Water levels in the bores were measured immediately after the completion of drilling. The shallow bores were sampled again in June 1993 as part of the non-point source pollution sampling program in the Perth Basin.

Table 2. Chemical analyses of groundwater samples

Bore no.	GSWA sample no.	Sample date	pH	Cond.	TDS	TH	TA	Ca	Mg	Na	K	CO_3	HCO_3	Cl	SO_4	NO_3	SiO_2	B	F	Formation
				(a)	*(b)*	*(c)*	*(d)*					mg/L								
LS1B	117434	12.05.93	7.5	221	1 240	327	185	65	40	335	27	<2	226	580	60	<1	15	0.1	0.1	Lesueur Ss
LS1C	117435	20.05.93	8.2	162	910	283	189	64	30	230	22	3	224	390	44	1	16	0.1	0.07	Tamala Ls/ Lesueur Ss
LS2A	117437	13.05.93	7.6	321	1 850	583	233	120	69	471	10	<2	284	830	184	<1	16	0.1	0.04	Lesueur Ss
LS2B	117438	13.05.93	7.9	233	1 300	493	248	130	41	290	7	<2	302	550	110	<1	16	0.1	0.03	Lesueur Ss
LS3A	117444	21.05.93	8.1	267	1 500	327	145	37	57	439	25	<2	177	740	97	<1	12	0.1	0.3	Cattamarra CM
LS3B	117439	20.05.93	7.6	1 380	8 270	1 680	339	112	340	2 600	22	<2	414	4 600	374	<1	14	0.12	0.6	Cattamarra CM
LS4A	117454	26.05.93	7.3	299	1 600	228	121	42	30	520	21	<2	148	800	105	<1	4	0.1	0.5	Cattamarra CM
LS4B	117447	24.05.93	12.1(e)	687	3 690	1 100	427	440	<1	890	75	11	<2	139	1 300	<1	5	<0.02	0.2	Cadda Fm
LS5A	117436	12.05.93	7.9	390	2 100	224	320	19	43	720	15	<2	391	1 020	76	<1	8	0.63	0.8	Lesueur Ss
LS5B	117417	23.05.93	7.8	149	800	307	236	82	25	173	4	<2	288	326	26	3	12	0.06	0.3	Tamala Ls
LS6A	117428	08.05.93	8.2	137	780	311	220	82	26	178	6	<2	268	310	29	1	15	0.06	0.2	Lesueur Ss
LS6B	117427	07.05.93	8.2	122	670	277	218	83	17	141	4	2	262	248	20	13	12	0.05	0.1	Lesueur Ss
LS7A	117442	17.05.93	7.6	183	1 010	209	122	31	32	301	18	<2	149	480	70	<1	5	0.03	0.8	Eneabba Fm
LS7B	117443	17.05.93	7.0	235	1 300	339	55	24	68	364	11	<2	67	670	95	5	29	0.02	0.3	Eneabba Fm
LS8A	86467	04.10.90	7.6	928	5 630	175	200	19	31	2 050	43	<2	244	2 900	408	1	54	0.3	1.3	Cattamarra CM
LS8B	86468	04.10.90	7.1	901	5 210	991	69	33	221	1 610	23	<2	84	2 800	408	<1	76	0.2	1.3	Cattamarra CM
LS9A	117440	13.05.93	7.5	119	670	116	74	17	18	206	14	<2	90	310	44	2	10	0.03	0.5	Lesueur Ss
LS9B	117441	13.05.93	6.7	173	960	226	27	8	50	271	8	<2	33	490	71	6	41	0.02	0.1	Lesueur Ss
LS10A	117408	15.04.93	7.9	695	3 970	1 070	329	200	140	1 110	3	<2	401	2 070	230	15	3	0.05	0.6	Tamala Ls
LS11A	117 430	10.05.93	7.0	87	490	72	57	4	15	150	16	<2	69	220	30	<1	19	0.03	0.2	Lesueur Ss
LS11B	117 431	10.05.93	7.6	196	1 100	242	89	21	46	323	14	<2	109	540	66	<1	36	0.02	0.2	Lesueur Ss
LS12A	117 409	06.04.93	7.1	4 640	33 900	6 320	166	390	1 300	10 300	390	<2	202	18 900	2 500	<1	<10	4.2	0.7	Tamala Ls
LS13A	117 423	29.04.93	7.4	247	1 360	207	60	17	40	420	16	<2	73	695	73	<1	65	0.16	0.2	Eneabba Fm
LS13B	117 424	29.04.93	7.0	513	2 900	527	66	30	110	890	26	<2	81	1 560	161	1	85	0.25	0.3	Eneabba Fm
LS14A	117 425	05.05.93	6.7	188	1 040	142	27	4	32	320	13	<2	33	534	65	1	52	0.07	0.2	Cattamarra CM
LS14B	117 426	05.05.93	6.9	95	540	97	32	16	14	150	6	<2	39	217	48	34	34	0.05	0.4	Cattamarra CM
LS15A	117 455	25.05.93	7.0	3 650	26 600	5 010	207	360	1 000	8 100	300	<2	252	14 800	1 910	1	<10	3.3	0.6	Eneabba Fm
LS15B	117 456	23.04.93	7.9	4 550	33 400	6 420	143	430	1 300	10 200	380	<2	175	18 500	2 500	<1	<10	4.1	0.6	Tamala Ls
LS16A	117 410	31.03.93	8.2	240	1 310	202	261	38	26	420	26	<2	318	554	69	<1	18	0.58	0.6	Cadda Fm
LS17A	117 411	22.04.93	7.8	343	1 900	328	158	36	58	590	30	<2	193	940	114	<1	39	0.21	0.3	Yarragadee Fm
LS17B	117 412	21.04.93	7.3	408	2 290	317	102	20	65	735	29	<2	124	1 180	142	<1	58	0.23	0.3	Yarragadee Fm

Notes:

All samples were obtained by airlifting
Analyses carried out by the Chemistry Centre of WA

(a) Conductivity: mS/m at 25°C
(b) TDS = total dissolved solids (value obtained by the summation of ions including half the bicarbonate)
(d) TH = total hardness as $CaCO_3$
(d) TA = total alkalinity
(e) sample contaminated by cement

Geology

Setting

The area is situated in the northern Perth Basin within the Dandaragan Trough, Cadda Terrace and the Beagle Ridge structural subdivisions of the basin (Figure 3). The Dandaragan Trough is the deepest part of the basin in the project area and contains a thick sequence of Permian to Late Jurassic sedimentary rocks. The Cadda Terrace is an area of intermediate-depth basement within the Dandaragan Trough along its western margin. The terrace is bounded by the Beagle Fault System to the west and the Eneabba Fault System to the east. The Beagle Ridge is a mid-basin ridge of shallow (about 1 km deep) basement between the Dandaragan Trough to the east and the Abrolhos Sub-basin to the west. Relatively flat-lying Permian to Jurassic sedimentary rocks are present on the Beagle Ridge. The project area is characterised by numerous north-trending faults and fault systems and includes, specifically, the Peron, Lesueur and Warradarge Faults and Beagle Fault System (Mory, 1994a, b, 1995).

Sediments of Triassic to Quaternary age were intersected during drilling (Table 2). Mesozoic units are unconformably overlain by up to 120 m of flat-lying Late Tertiary–Quaternary sediments of the coastal plain collectively referred to as the superficial formations (Allen, 1976). Possible earlier Tertiary sediments are represented by channel sand encountered in Eneabba Line 6 (Commander, 1978). The surface of the unconformity between the superficial formations and the Mesozoic formations is irregular and slopes from about 80 m AHD near the Gingin Scarp to about -30 m AHD along the coast (Figure 3). The gradient of the unconformity surface is steep along the Gingin Scarp and flattens substantially to the west within 5 km of the scarp.

Stratigraphy

In the investigation area, Phanerozoic sedimentary rocks of Permian to Quaternary age are developed over Precambrian crystalline basement, which was intersected in petroleum wells. Sediments intersected during the investigation were of Mesozoic and Quaternary age (Figures 3, 4 and 5). The Mesozoic units are identified by palynological analysis (Backhouse, J., unpublished reports *in* Kern, 1994). The stratigraphic succession intersected by the drilling is given in Table 3.

Table 3. Stratigraphic succession

	Age	Formation	Maximum thickness penetrated (metres)	Lithology
		Miscellaneous deposits	14	sand, silt, clay, peat, marl
	Holocene			
		Safety Bay Sand	2	sand
QUATERNARY				
	L. Pleistocene	Tamala Limestone	49	limestone, sand
	M.–L. Pleistocene	Bassendean Sand	?8	sand
	Pleistocene	Guildford Formation	33	sand, clay
TERTIARY	Pliocene	Yoganup Formation	(a)	sand, clay
~ ~ ~ ~ ~ ~ ~ ~ ~	~ ~ ~ ~ ~ ~ ~ ~	unconformity ~ ~ ~ ~	~ ~ ~ ~ ~ ~ ~ ~	~ ~ ~ ~ ~ ~ ~ ~
	Middle–Late	Yarragadee Formation	77	sandstone, shale
	Middle	Cadda Formation	76	shale, siltstone, sandstone
JURASSIC				
	Early–Middle	Cattamarra Coal Measures	91	sandstone, siltstone, shale
	Middle–Late	Eneabba Formation	88	sandstone, siltstone, shale
	Middle–Late	Lesueur Sandstone	88	sandstone
TRIASSIC	late Early–Middle	Wodadda Formation	10	sandstone, siltstone,
	Early	Kockatea Shale	10	shale, siltstone,

(a) Not intersected

Permian

Permian sediments, which are predominantly argillaceous, have been intersected in petroleum and coal exploratory bores and are present in the subsurface in the investigation area. The Caryngina Formation subcrops beneath Quaternary sediments on the Beagle Ridge (Figures 4 and 5). The Holmwood Shale and Carynginia Formation are mainly shale with minor sandstone. The Irwin River Coal Measures, with minor coal, and the High Cliff and Beekeeper Formation are thin sandstone formations (Mory, 1994a, b).

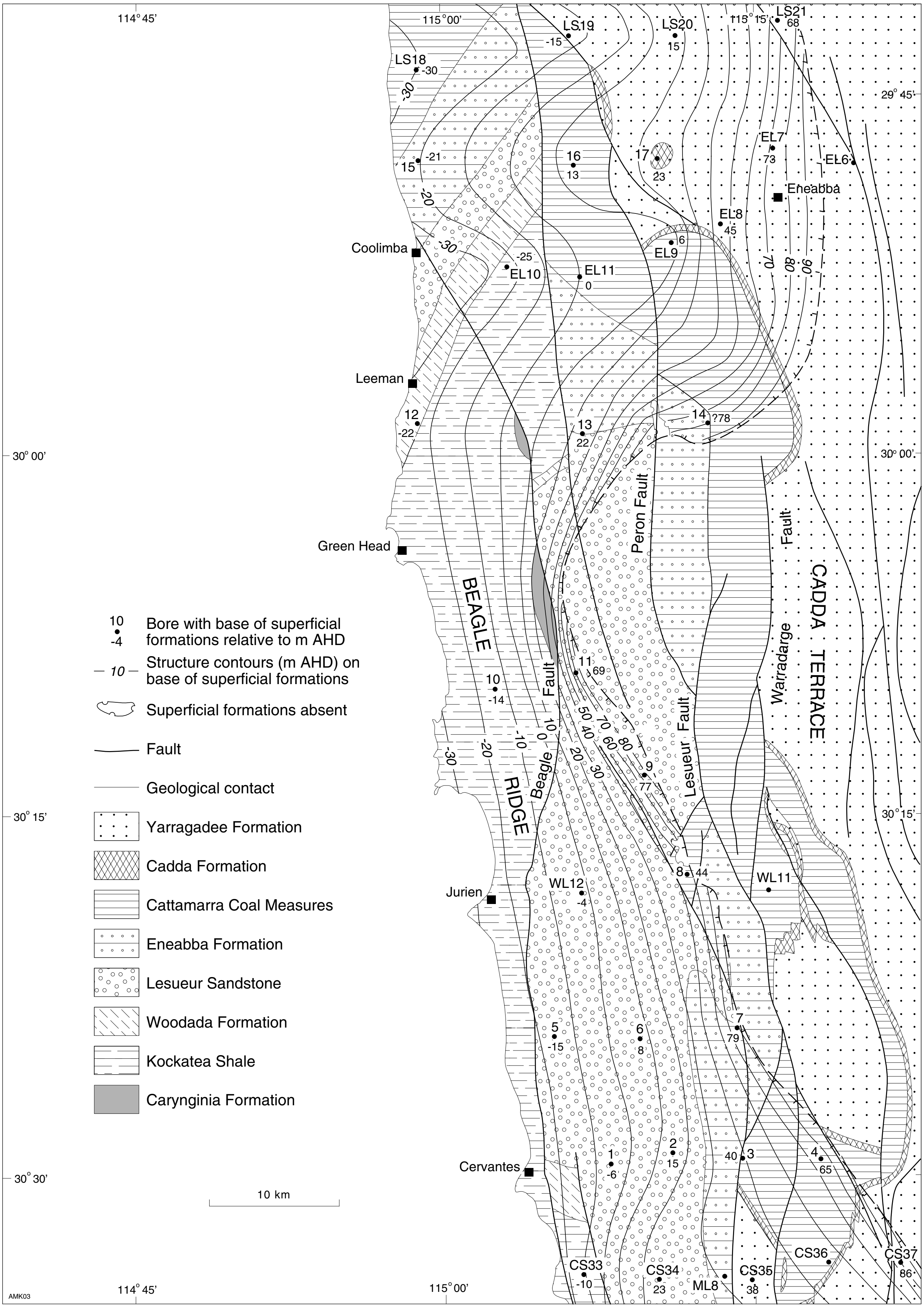

Figure 3. Subcrop map and contours on base of superficial formations

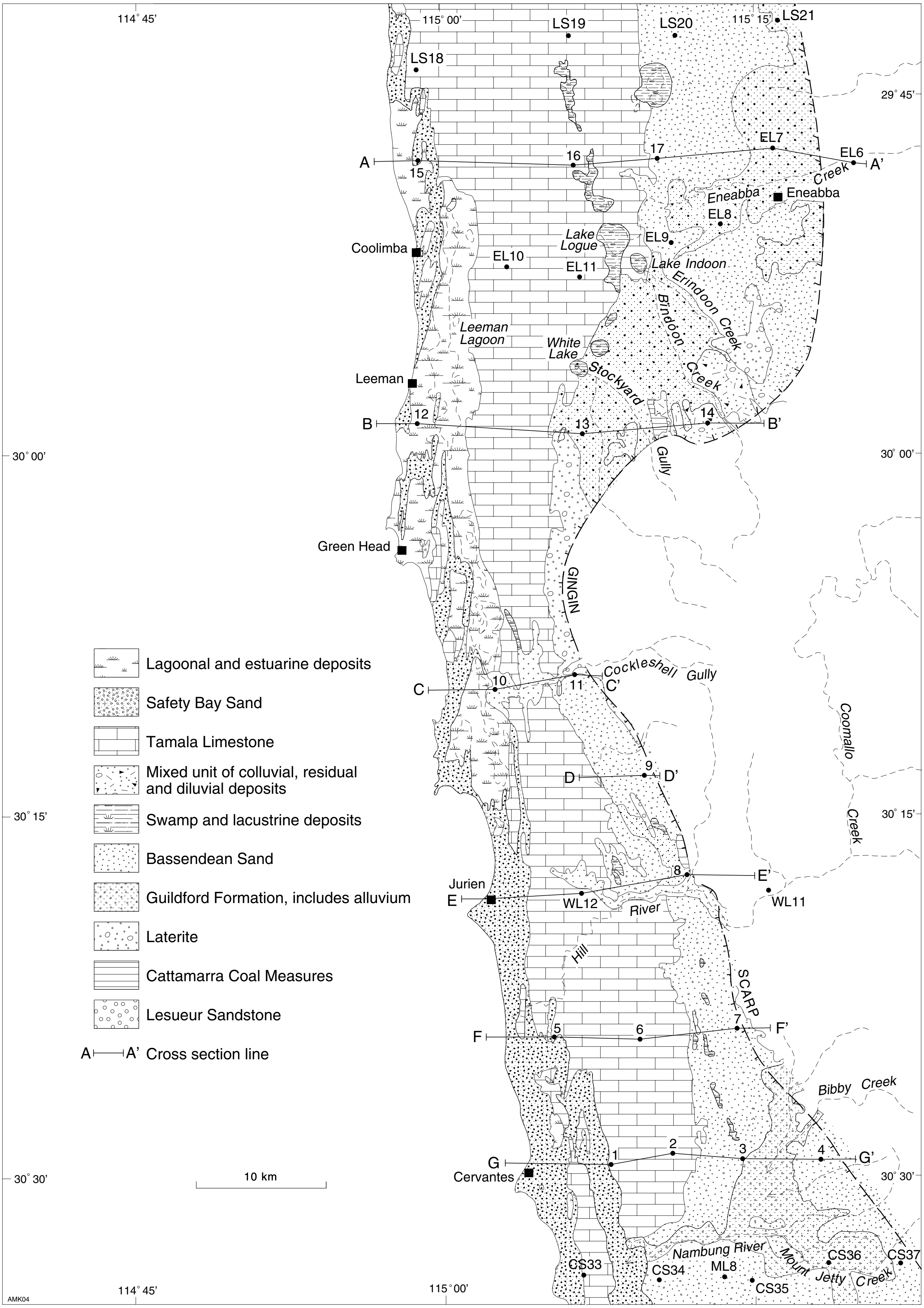

Figure 4. Surface geology

Triassic

Kockatea Shale (Early Triassic): The Kockatea Shale was intersected at shallow depth at site LS10 on the Beagle Ridge where it is unconformably overlain by Quaternary sediments. The unit unconformably overlies the Permian Carynginia Formation (not intersected). The Kockatea Shale is characterised by shale, micaceous siltstone, and minor sandstone and limestone. In bore LS10A the formation consists mostly of shale with thin beds of slightly to fairly micaceous siltstone. The upper section of the formation in bore LS10A is weathered to an olive-brown, medium grey and yellow banding, and the lower section is medium to dark grey. The Kockatea Shale is 1060 m thick in Cadda 1 well (7 km north of LS7). Spore and pollen indicate a shallow-marine depositional environment of Anisian to Scythian age.

Woodada Formation (late Early to Middle Triassic): The Woodada Formation was intersected only at site LS12 on the Beagle Ridge. The formation consists of interbedded fine-grained sandstone and siltstone lying conformably between the Kockatea Shale below and the Lesueur Sandstone above. At site LS12 the formation consists of fine-grained sandstone with minor siltstone. The sandstone is thinly banded and of yellow, buff and light grey colour in the upper section becoming medium to light grey at depth. The sandstone is poorly consolidated and includes traces of heavy minerals. The Woodada Formation is 276 m thick in BMR10 bore (3.5 km south of LS15) on the Beagle Ridge and up to 320 m thick in petroleum wells in the northern part of the investigation area. Plant fossils suggest that the Woodada Formation is a paralic deposit, and represents the regressive phase between the marine Kockatea Shale and the continental Lesueur Sandstone.

Lesueur Sandstone (Middle to Late Triassic): The Lesueur Sandstone is present in the westernmost part of the Dandaragan Trough and on the Beagle Ridge north of Leeman. The formation outcrops north and east of site LS11, along the Hill River, and on the west flank of Mount Lesueur. It conformably overlies the Woodada Formation and is conformably overlain by the Eneabba Formation.

The Lesueur Sandstone was intersected at six sites (LS1, 2, 5, 6, 9 and 11) and consists of light-grey, medium-to very coarse-grained, cross-bedded quartz sandstone with siltstone and conglomerate. In drill cores the upper section of the formation is commonly weathered to a yellow-buff colour; the lower section is locally well cemented and hard. Minor carbonaceous shale with thin coal seams were intersected in bore LS2A. The Lesueur Sandstone is about 600 m thick in Watheroo Line 12 and reaches a thickness of 1201 m in Cadda 1. The formation is believed to be a fluvial unit.

Jurassic

Eneabba Formation (Early Jurassic): In the investigation area the Eneabba Formation (Mory, 1994a, b, 1995) subcrops mostly east of the Beagle Fault system, but also occurs on the Beagle Ridge north of Leeman and outcrops on the west flank of the Gairdner Range. This unit lies conformably between the Lesueur Sandstone and the Cattamarra Coal Measures.

The Eneabba Formation, which was intersected at 4 sites (LS7, LS13–15), consists of fine- to coarse-grained felspathic sandstone interbedded with multicoloured siltstone and claystone. Minor grey carbonaceous shale and thin coal seams are also present. In bore LS15A the formation consists of dark grey-green, slightly micaceous shale interbedded with thinly banded dark- and medium-grey siltstone and minor well cemented sandstone with traces of carbonaceous matter. The Eneabba Formation is up to 744 m thick in Woolmulla 1 well (5 km south of LS14). The formation is fluvial in origin and the spores and pollen assemblages indicate a Pleinsbachian to Early Toarcian age.

Cattamarra Coal Measures (Early–Middle Jurassic): The Cattamarra Coal Measures (Mory, 1994a, b, 1995) occurs east of the Beagle Fault system except north of Leeman where it subcrops on the Beagle Ridge. The formation outcrops in the Gairdner Range east of the Lesueur Fault. Contacts with the underlying Eneabba Formation and the overlying Cadda Formation are conformable.

The Cattamarra Coal Measures was intersected at sites LS3, LS4 and LS8, and consists of sandstone with inter-bedded, siltstone, claystone, carbonaceous shale and coal. The formation is distinguished from the underlying Eneabba Formation by the presence of thick carbonaceous siltstones and mudstones. In the investigation area the sandstone is medium grey in colour, often clayey, and mostly medium to coarse grained. The siltstone and shale are dark grey, sometimes carbonaceous and often laminated. Site LS4 is situated within the Wongonderrah coal deposit where individual coal seams are up to 2.3 m thick. The Cattamarra Coal Measures is approximately 300 m thick in the Woodada gasfield. The thick sandstone beds are most likely to be fluvial in origin whereas the carbonaceous siltstone and sandstone probably reflect a variety of nearshore to fluvial environments.

Cadda Formation (Middle Jurassic): The Cadda Formation subcrops in small areas on the Dandaragan

Trough and outcrops between Cadda Downs and Mount Benia in the Gairdner Range. The formation lies conformably between the Cattamarra Coal Measures and Yarragadee Formation.

The Cadda Formation was intersected at sites LS4, LS16 and LS17, and consists of shale, siltstone, and medium- to very coarse-grained sandstone, grading in places into sandy, shaly limestone. In bore LS16A the shale is locally shelly and the siltstone is slightly micaceous and includes minor carbonaceous matter. The Cadda Formation is 230 m thick in Coomallo 1 (22 km east of LS8) and the thickness increases to the northeast into the Dandaragan Trough. The formation is regarded as a shallow-marine to paralic deposit, and spores and pollen suggest a Bajocian (Middle Jurassic) age for the unit.

Yarragadee Formation (Middle–Late Jurassic): The Yarragadee Formation occurs in the northeast of the investigation area, and east of the Warradarge Fault and is overlain by Tertiary to Quaternary deposits. The formation conformably overlies the Cadda Formation.

The Yarragadee Formation was intersected only at site LS17 and it consists of interbedded fine- to coarse-grained felspathic sandstone, siltstone and claystone with minor conglomerate and coal. The sandstone consists of fine- to very coarse-grained, angular to subangular, poorly sorted quartz sand. The upper section is weathered to a yellow-buff colour and the shale contains traces of carbonaceous matter. The Yarragadee Formation reaches a thickness of about 2970 m in Coomallo 1 east of the investigation area. The formation is largely a fluvial deposit, but thicker shaly sections may represent a lacustrine environment of deposition.

Tertiary

Channel sand (Tertiary): Channel sand deposits occur locally in the valley of Eneabba Creek and have been encountered in EL6 and nearby bores drilled for mineral-sand processing (Commander, 1978, 1980, 1981). They are up to 153 m thick in EL6 near the point of emergence of the Eneabba Creek through the Gingin Scarp. The deposits are well sorted medium- to coarse-grained sands containing minor clay and accessory heavy minerals. The channel is probably associated with the palaeodrainage system on the Dandaragan Plateau to the east and the sand is most likely of alluvial origin.

Laterite and associated sand (Late Oligocene–Early Miocene): Laterite and associated sand are developed on top of the weathered Mesozoic formations and widespread along the foot of Gingin Scarp (Figures 4 and 5). The typical laterite profile consists of leached quartz sand overlying 2–3 m of pisolitic to massive ferruginous laterite, which in turn overlies a zone of weathered parent rock that may be up to 40 m thick (Mory, 1994a, b). Laterite and associated sand were not intersected during the drilling program.

Yoganup Formation (Late Tertiary–Early Pleistocene): The Yoganup Formation extends sporadically along the foot of the Gingin Scarp where it unconformably overlies the Yarragadee Formation or older Mesozoic formations and is unconformably overlain by the Guildford Formation.

The formation was not intersected during the drilling program although it occurs about 2 km southwest of site LS8 in the Jurien heavy mineral deposit and 2 km east of site LS14 (Figure 5) in the Eneabba heavy-mineral deposit (Mory 1994a, b). The formation consists of orange-brown, yellow, poorly sorted, subangular to subrounded fine to very coarse sands and clayey sands with concentrations of heavy minerals in places. The sands are leached and ferruginized and are often associated with lenticular beds of kaolinized felspar. Nidagal (1995) commonly found it difficult to define accurately the boundary between the Yoganup Formation and the underlying Yarragadee Formation because of their lithological similarities. The Yoganup Formation is a shoreline deposit representing a buried prograding coastline of dunes, beach ridges and deltaic deposits.

Quaternary

Guildford Formation (Pleistocene): The Guildford Formation is present in the subsurface in the eastern parts of the project area and unconformably overlies Mesozoic strata or the Yoganup Formation where it is present. On the coastal plain the formation is unconformably overlain by the Bassendean Sand and possibly by the Tamala Limestone, and along the Gingin Scarp by colluvium.

The Guildford Formation was intersected at eight sites and reaches a maximum thickness of 33 m in bore LS13. The formation is characterised by both a sandy and clayey facies, the latter occurring only along the Gingin Scarp where it interfingers with the sandy facies to the west. The sand is light grey and buff with fine to coarse, subangular to subrounded, very poorly sorted quartz. Accessory minerals are generally not abundant, although minor heavy minerals and feldspar may be present. The clays occurring close to the Gingin Scarp are mainly multi-coloured yellow, mauve, red and brown. Typically, a hard to moderately hard limonite-cemented sand (‘coffee rock’)

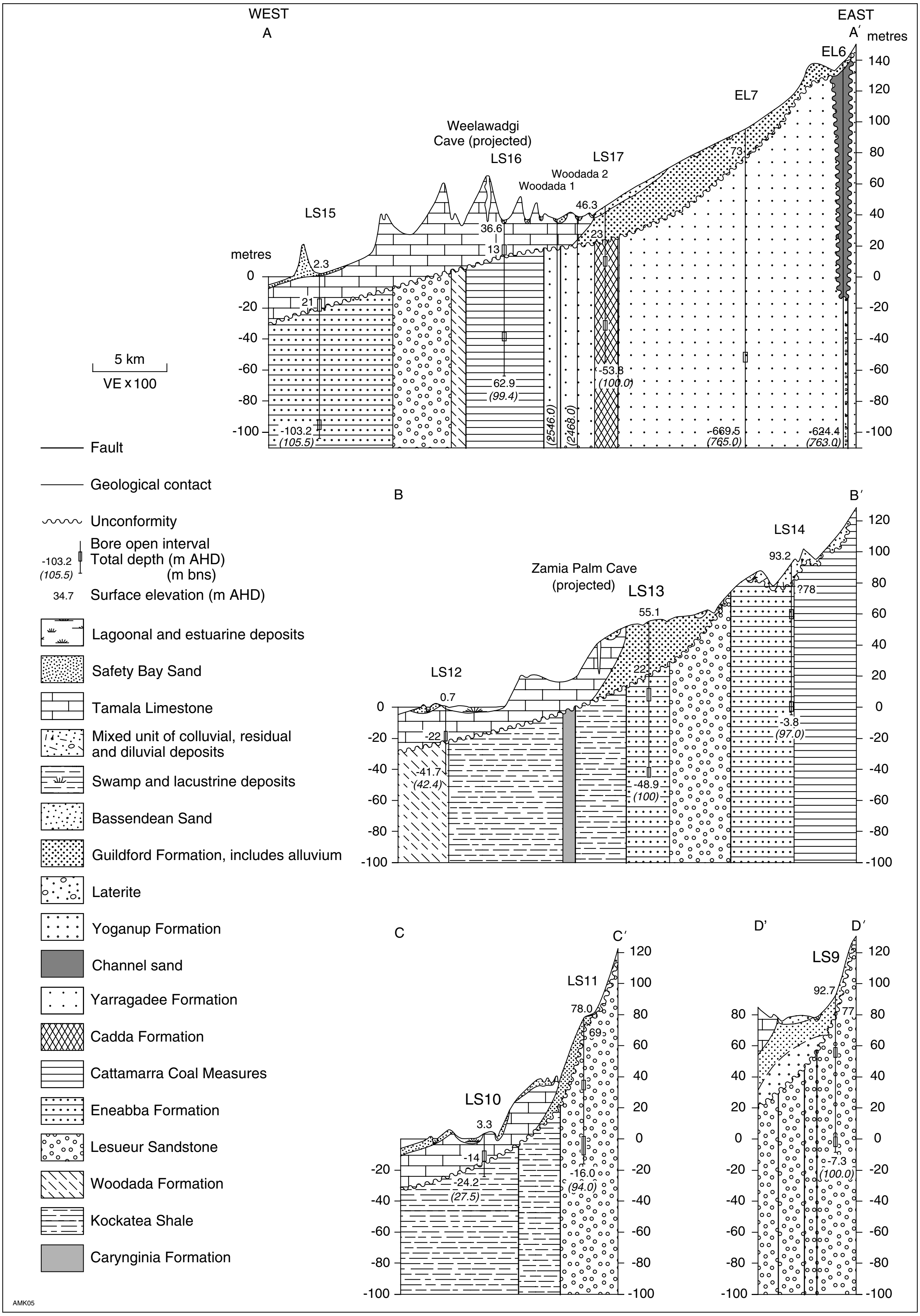

Figure 5. Geological cross sections (see Section G for legend)

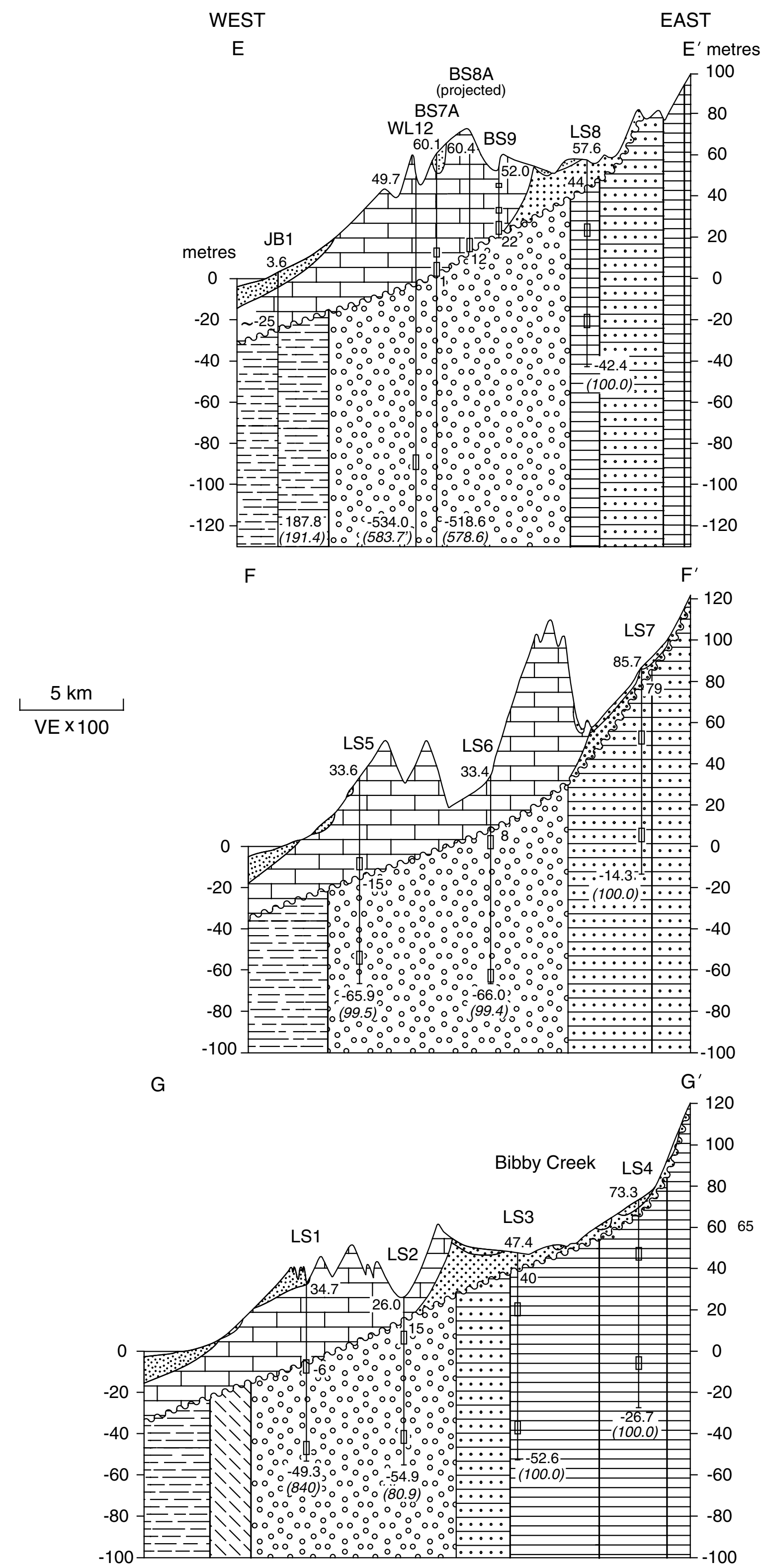

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Figure 5. (*continued*)

is developed at or near the watertable. The Guildford Formation is presumably of fluvial origin.

Bassendean Sand (Middle–Late Pleistocene): The Bassendean Sand forms the Bassendean Dunes, a series of low sandhills over the central region of the coastal plain. The formation unconformably overlies the Guildford Formation and is unconformably overlain by the Tamala Limestone in the west.

The Bassendean Sand was intersected at three sites (LS4, 7 and 17). Although the thickness of the formation varies considerably, depending on the topography, the average is about 5 m with a maximum thickness of about 30 m. The formation is pale grey to white and fine to coarse grained, but predominantly medium grained. This unit consists of moderately sorted, subrounded to rounded quartz sand, and commonly has an upward-fining progression in grain size. Fine-grained, black, heavy minerals are commonly scattered throughout the formation in thin layers, probably indicating a shallow marine origin. There is commonly a thin layer of ferruginized sand ('coffee rock') at the watertable. The stratigraphic relationship with the Guildford Formation indicates that the formation was deposited as eolian sand dunes.

Tamala Limestone (Late Pleistocene): The Tamala Limestone, which outcrops extensively along the coast and adjacent islands, unconformably overlies the eroded surface of Triassic to Jurassic formations in the west and possibly the Bassendean Sand along its eastern margin. The formation is overlain by the Safety Bay Sand in the west and may interfinger with the Bassendean Sand in the east.

The Tamala Limestone was intersected at ten sites. Thickness of the unit, which varies greatly depending on the topography, is 49 m at site LS5 but probably reaches 120 m at Verne Hill, situated 12 km northeast of Cervantes.

The Tamala Limestone is buff to pale yellow, weathering to grey, and consists of quartzo-calcareous sand, commonly cemented into limestone. The carbonate fragments are mainly foraminifers and mollusc shells. Minor components include accessory minerals (up to 5%), glauconite, and felspar. The limestone varies from strongly lithified to friable. A hard calcrete horizon ('capstone') occurs in places and may be overlain by fossil soil, and underlain by softer limestone with abundant fossil root structures. The formation also shows large-scale eolian cross-bedding.

The Tamala Limestone contains numerous solution channels and cavities, particularly in the zone where the watertable fluctuates, and in some areas exhibits karst structures. Cave systems are well developed in the limestone at a number of localities in the Drovers Cave National Park and in nature reserves east of Leeman and Coolimba. Marine algae were found in solution channels in bore LS12A, probably washed in by tides (Kern, 1994). The Tamala Limestone was deposited as coastal sand dunes (lime-sand eolianite).

Safety Bay Sand (Holocene): The Safety Bay Sand lies along the coastal margin as stable and mobile eolian dunes of the Quindalup Dune System. It extends to about 50 m above sea level and unconformably overlies the Tamala Limestone. The Safety Bay Sand was intersected only at site LS1 where it is about 2 m thick and unconformably overlies the Tamala Limestone. The formation consists of cream to buff, unlithified, fine- to medium-grained quartz and calcareous sand with shell fragments, and traces of heavy minerals. The Safety Bay Sand is still being deposited as eolian sand dunes.

Miscellaneous deposits: A number of additional Quaternary units have been recognised in the project area. Some of these are poorly defined and have not yet been studied in any detail (Figures 4 and 5).

Alluvial deposits occur over large areas in the project area, mostly on the modern flood plains over the Bassendean Dunes and Eneabba Plain. They consist of sand and silt, and reach 20 m in thickness. These deposits have been included with the Guildford Formation in Figures 4 and 5.

A mixed unit of colluvial, residual and diluvial deposits occurs along the Gingin Scarp and comprises gravel and quartz sand associated with silt, clay and laterite clasts derived from the erosion of the laterite capped scarp. This residual unit is about 15 m thick at site LS14.

Lacustrine and swamp deposits formed in areas without external drainage in the central part of the coastal plain. The deposits consist largely of clay and peat, but some also contain diatomite where there has been low clastic sediment input. These sediments are still in the process of deposition and rarely exceed 3 m in thickness.

Lagoonal and estuarine deposits consist of marl, shell beds, clay and silt. These sediments were intersected at site LS12 where they form a veneer over the Tamala Limestone. Beneath Leeman Lagoon these deposits are up to 5 m thick and include gypsum mud, gypsite and, in places, halite at the top (Arakel, 1980).

Hydrogeology

Flow systems

There are two main regional groundwater flow systems in the area; an unconfined flow system in the superficial formations, and an unconfined to confined flow system in the Mesozoic Formations (Figure 6). These two flow systems are locally interconnected where there are no separating confining units. All the Mesozoic units except the Lesueur Sandstone are multilayered aquifers, and are in hydraulic continuity where they are juxtaposed by faults.

Superficial formations

The superficial formations form a complex, uniform, multilayered aquifer, extending throughout the coastal plain west of the Gingin Scarp. The sediments that constitute the aquifer range from predominantly clayey (clayey facies of the Guildford Formation) in the east adjacent to the Gingin Scarp, through a sandy succession (Bassendean Sand and sandy facies of the Guildford Formation) in the central coastal plain, to sand and limestone (Safety Bay Sand and Tamala Limestone) along the coast. Over much of the area the aquifer directly overlies sedimentary rocks of Triassic to Jurassic age. The superficial aquifer has a maximum saturated thickness of about 35 m in Eneabba Line 9, but the average saturated thicknesses is 10 m. However, in places the superficial formations are completely unsaturated, such as in the area around the town of Eneabba (Figure 7). Aquifer transmissivity varies significantly across the coastal plain between areas of high clay content in the clayey facies of the Guildford Formation and those of the more karstic Tamala Limestone. The transmissivity typically increases from east to west, where the superficial formations consist predominantly of sand and limestone.

Groundwater flow is mainly in a westerly direction. Downward leakage occurs in the east, whereas there is upward discharge from the Mesozoic aquifers into the superficial formations in the west (Figure 8).

Watertable configuration

The watertable configuration depends mainly on the topography but also on the hydraulic conductivity (permeability) of the sediments and location within the groundwater flow system. The configuration of the watertable is shown by the watertable-contour map, drawn for May 1993 (Figure 9). The watertable contours are sub-parallel to the coast and the predominant flow directions are to the west and southwest. The watertable slopes from a maximum of 80.7 m AHD in bore LS9B towards the coast where the groundwater is discharged into the ocean over a saltwater interface. In the eastern area of clayey sediments, the hydraulic conductivity is generally small (<10 m/d) and the hydraulic gradients are relatively steep in comparison with those in the central sandy area. In the coastal area the hydraulic conductivity is much higher (10–50 m/d) and the hydraulic gradients are relatively uniform.

At the contact between the combined Bassendean Sand and Guildford Formation, and the Tamala Limestone, the hydraulic gradients are relatively steep due to the marginally lower hydraulic conductivities of finer grained sand at the eastern margin of the Tamala Limestone, and also in part to the higher hydraulic conductivity to the west resulting in a draining effect. The watertable drops about 60 m between sites LS11 and LS10 over a distance of 6 km. A similar gradient occurs between sites LS7 and LS6 where the watertable falls from 87 m AHD to 16 m AHD over 7 km. At the coast the hydraulic gradient is very low owing to the high hydraulic conductivity of the Tamala Limestone.

The water levels are highest during September–October after winter rainfall and lowest in March–April at the end of summer.

Recharge

Recharge to the superficial formations is mainly by direct infiltration of rainfall and from episodic runoff originating on the Arrowsmith Region. Seasonally, groundwater recharge occurs from the Hill River downstream of Canover Pool. Surface runoff enters the Tamala Limestone through caves and tunnels in times of flood from Stockyard Gully and the western edge of Lake Logue (Commander, 1981). Recharge rates vary considerably, depending on landuse and lithology. There is likely to be a general reduction in rainfall infiltration toward the east where the sediments are more clayey.

Along the coastal strip there is significant upward leakage from the underlying Mesozoic formations. At site LS11

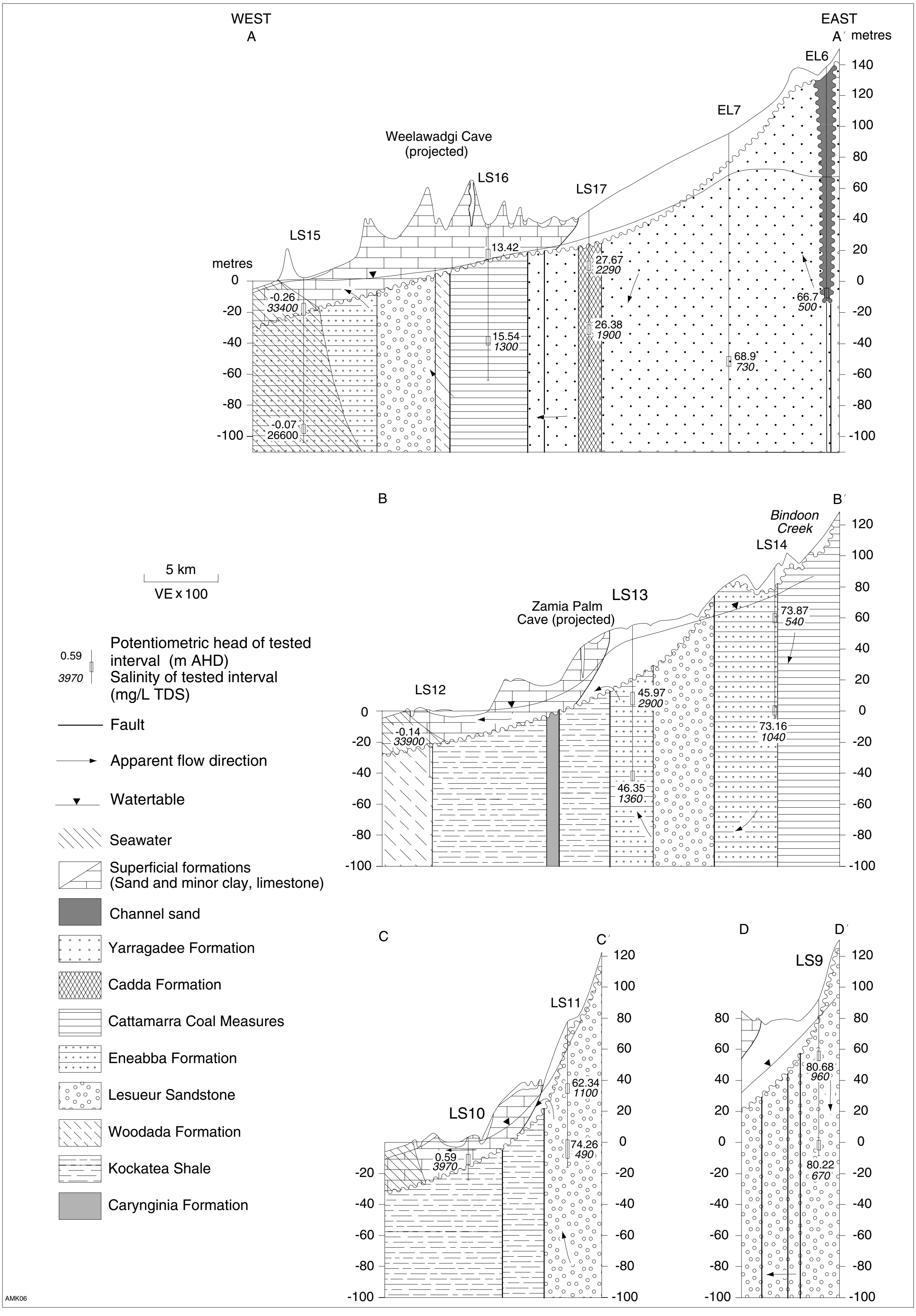

Figure 6. Hydrogeological cross sections

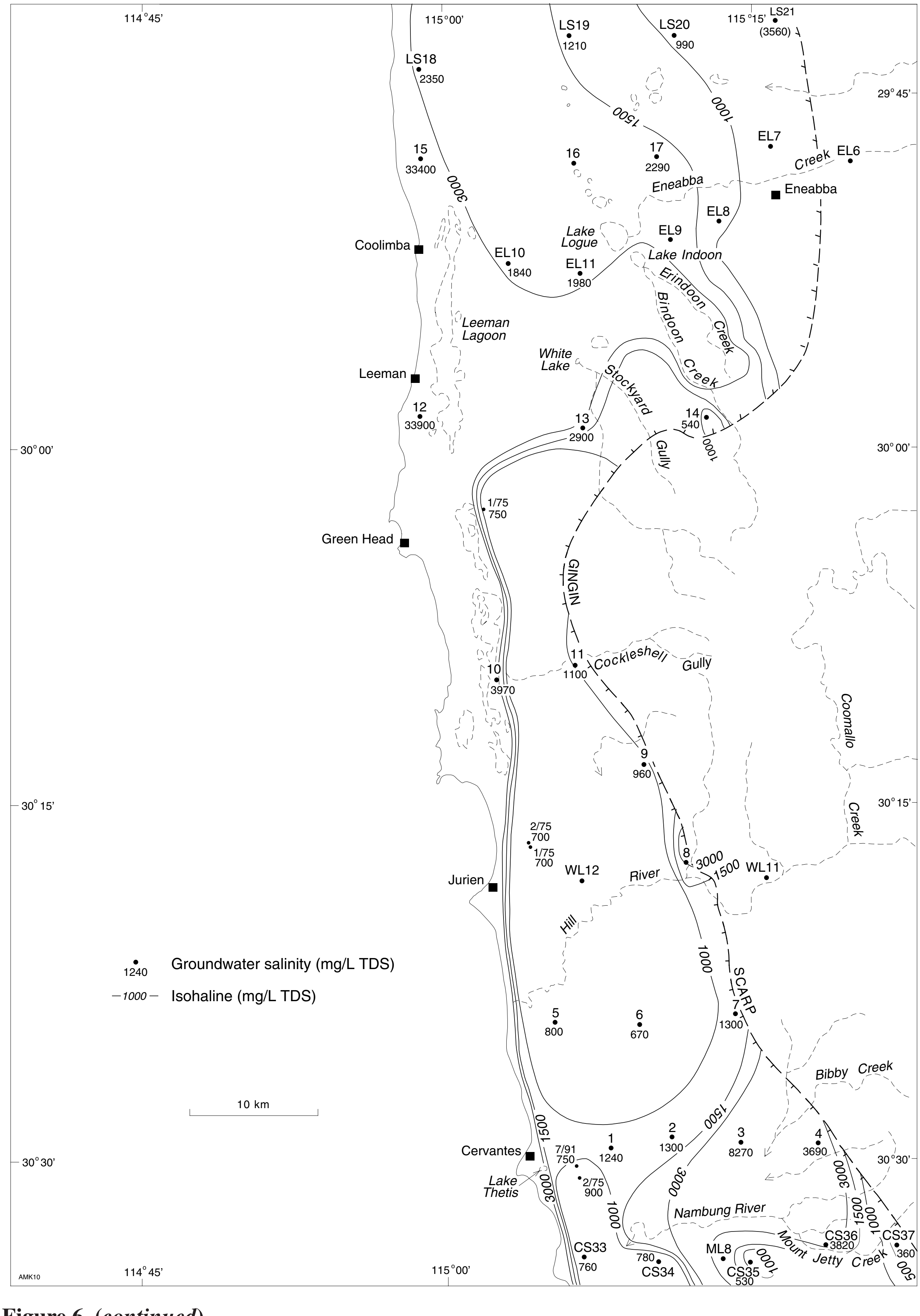

Figure 6. (*continued*)

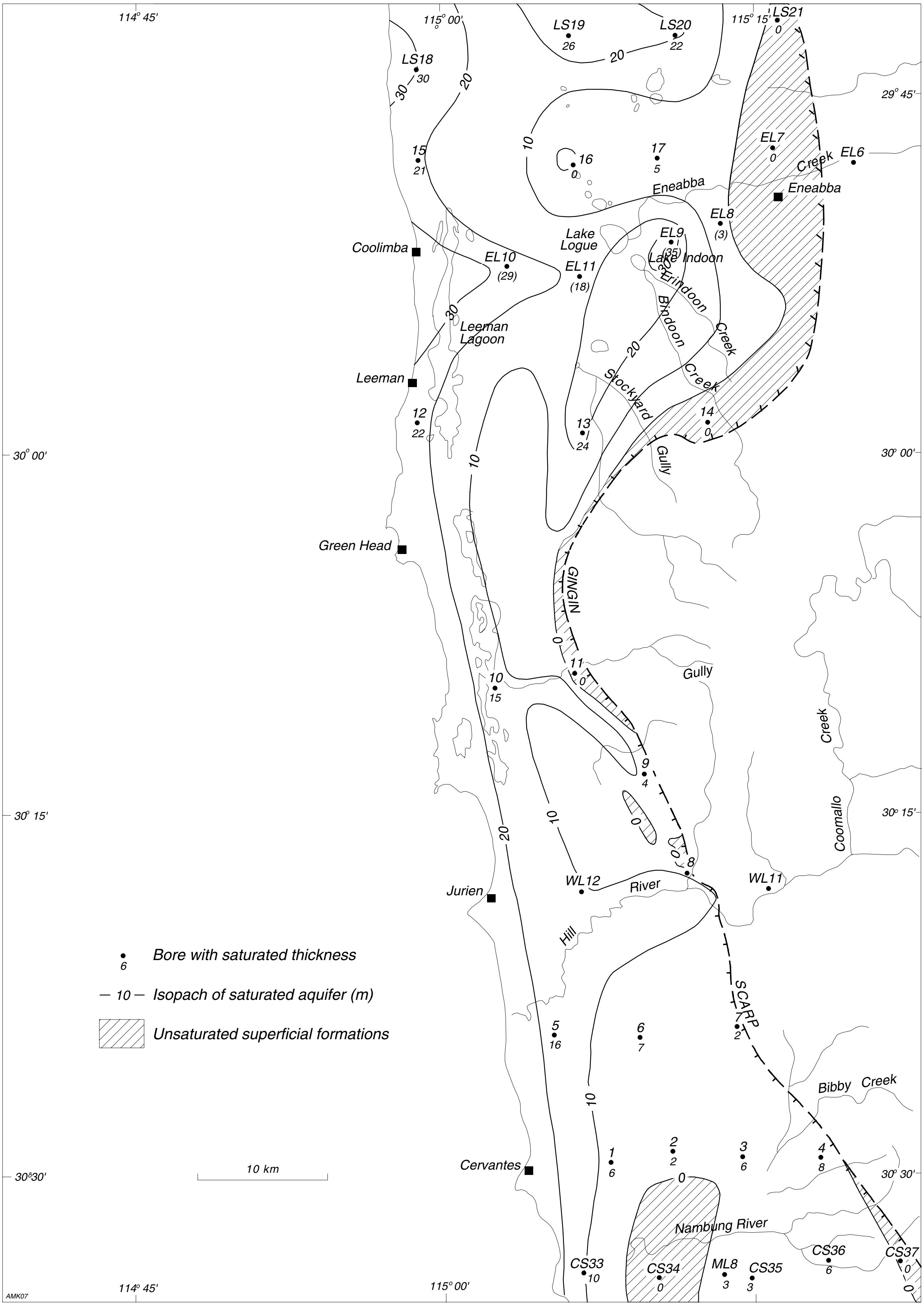

Figure 7. Superficial formations: saturated thickness

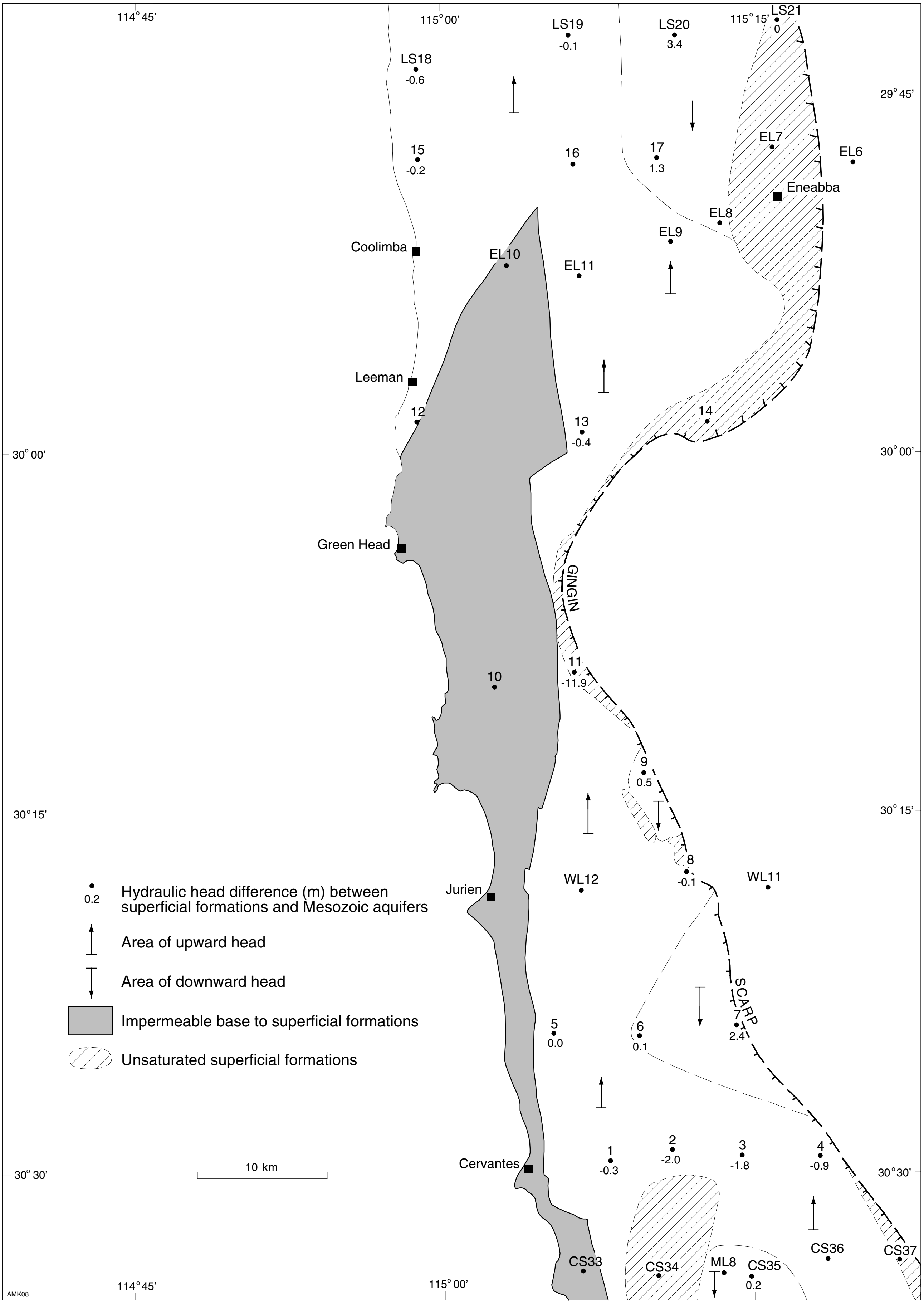

Figure 8. Hydraulic-head difference between superficial formations and Mesozoic aquifers

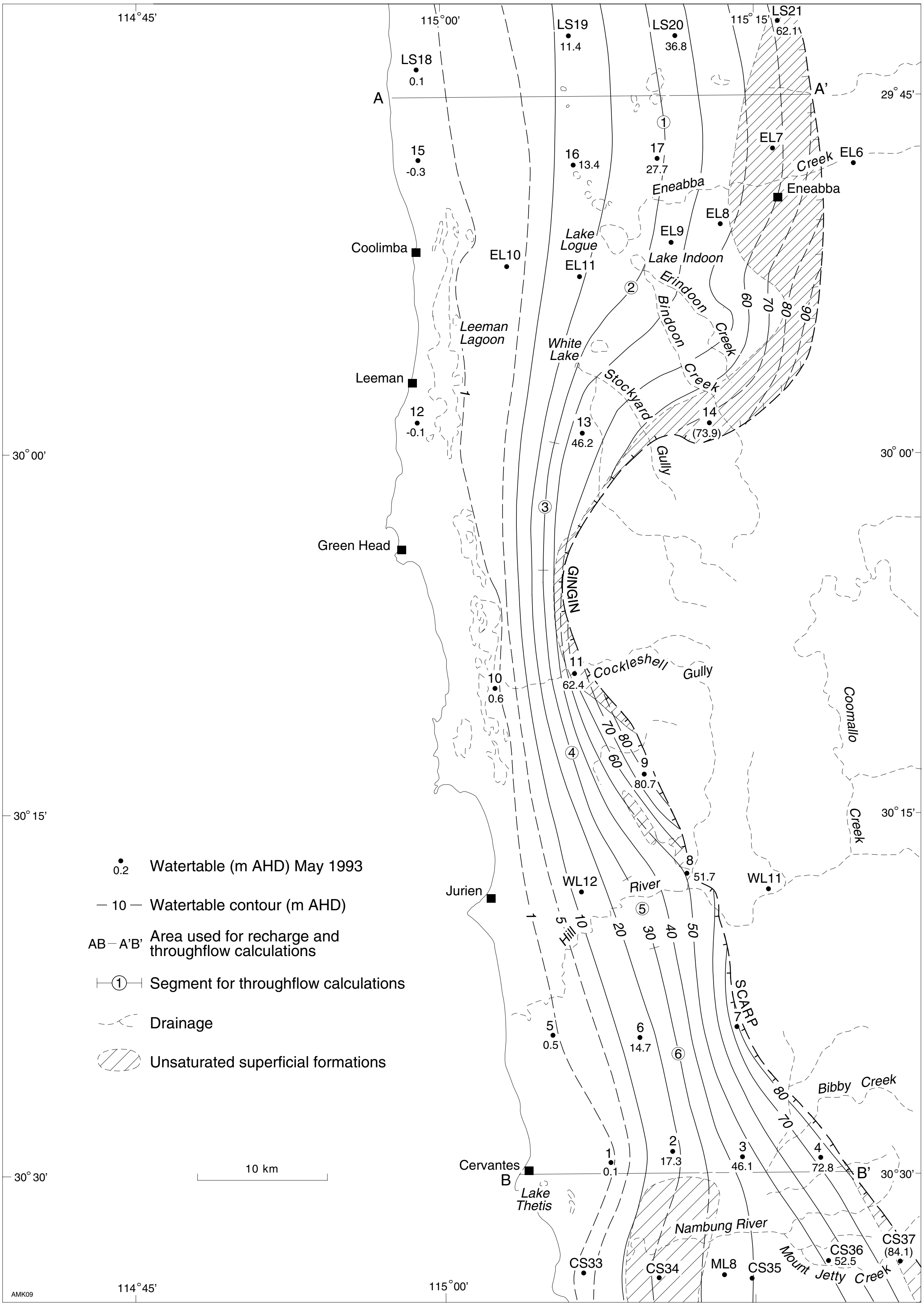

Figure 9. Watertable contours in the superficial formations

Table 4. Throughflow past 30 m watertable contour

Segment (Fig. 9)	Average saturated thickness **b** (m)	Contour segment length **l** (km)	Hydraulic gradient **i** (x 10^{-3})	Hydraulic conductivity **k** (m/day)	Throughflow Q = kbil (m^3/day x 10^3)	Annual throughflow (m^3/year x 10^6)
1	8	8	3	20	3.8	1.4
2	20	21	4	20	33.6	12.3
3	8	10	10	20	16.0	5.8
4	8	25	10	20	40.0	14.6
5	12	6	5	20	7.2	2.6
6	7	18	7	20	17.6	6.4
				Totals	**118.2**	**43.1**

there is an upward hydraulic-head gradient of about 11.9 m over an interval of 50 m in the top of the Lesueur Formation (Figures 7 and 8). Elsewhere vertical gradients are much lower.

Throughflow

The groundwater in the superficial formations flows westward before being discharged into the coastal lakes and the Indian Ocean. Groundwater throughflow is calculated past the 30 m watertable contour as this contour coincides approximately with the eastern limit of the Tamala Limestone and karstic effects can be ignored. Watertable contours for May 1993 (Figure 9) were used to estimate the hydraulic gradient, and an average hydraulic conductivity of 20 m/d was adopted for the Guildford Formation. The aquifer section A–B was divided into six segments and aquifer thickness and hydraulic gradients were determined from Figures 5 and 7. The throughflow past the 30 m watertable contour was calculated using the Darcy equation (Q = kbil) and the results given in Table 4. The total throughflow past the 30 m contour across a flow section of 88 km is about 118.2 x 10^3 m^3/day. This is equivalent to 43.1 x 10^6 m^3/year. In terms of rainfall the throughflow is equal to about 11% of the average annual rainfall of 560 mm on the area of 672 km^2 east of the 30 m watertable contour on the coastal plain (between AA' and BB' in Figure 9). This is almost double the 6% estimated by Commander (1981) and the 6.5% for the coastal plain north of Leeman estimated by Nidagal (1995); however, there is groundwater flow into the area from Mesozoic Formations in the Arrowsmith Region.

A large amount of recharge should also take place in the area between the 30 m watertable contour and the coast. Rainfall recharge of 6% on this area of 1013 km^2 represents 39.7 x 10^6 m^3/year. The total annual throughflow to the ocean is therefore about 82.8 x 10^6 m^3/year and discharge to the ocean about 0.97 x 10^6 m^3/km. These figures are probably conservative because no account is taken of upward leakage from the Mesozoic aquifers.

Discharge

Groundwater moves very slowly through the superficial formations and discharge occurs mainly along the shoreline above a saltwater wedge. Significant discharge also takes place to the salt lakes between Jurien and Coolimba, often through springs. Minor discharge occurs along some sections of water courses. Canover Pool, located in the Hill River, is most likely maintained by groundwater discharge. The watertable contours on Figure 9 also imply seasonal groundwater discharge to the Hill River upstream of Canover Pool. In addition, discharge occurs by evaporation from wetlands, transpiration from vegetation, leakage into underlying aquifers where there are downward heads and where confining beds are absent, and by abstraction of groundwater by bores. At the coast, groundwater discharge takes place above a saltwater wedge. The interface between fresh groundwater and seawater was intersected at sites LS12 and LS15.

Storage

The volume of groundwater in storage was estimated from isopachs of the saturated thickness (Figure 5) together with estimated specific yields of 0.3 for the Tamala Limestone and 0.2 for the Bassendean Sand and Guildford Formation (sandy facies). The volume of groundwater held in storage within the superficial formations has been calculated by multiplying the saturated aquifer volume by estimated values of specific yield. The total groundwater in storage within the superficial formations between AA' and BB' (Figure 7) is about 5.6 x 10^9 m^3.

Salinity

The groundwater salinity at the watertable shown in Figure 8 ranges from about 540 to 33 900 mg/L total dissolved solids (TDS). Fresh groundwater with a salinity of less than 1000 mg/L TDS occurs only in one-third of the investigation area. Fresh groundwater is restricted to recharge areas, particularly at the eastern edge of the coastal plain adjacent to the Gingin Scarp, such as in the Eneabba area, where it is derived entirely from direct rainfall infiltration, and in the Tamala Limestone east of Jurien where it is also recharged by upward flow from the underlying Lesueur Sandstone. Salinity typically increases in the direction of groundwater flow and with depth. Groundwater salinity is highest at discharge boundaries formed by salt lakes, and in the lower catchment area of the Nambung River where there is saline groundwater discharge from the Eneabba Formation and Cattamarra Coal Measures.

The upward discharge of brackish groundwater from the Mesozoic aquifers into the superficial formations causes the salinity of the groundwater in the superficial formations locally to exceed 8000 mg/L TDS on the Nambung River flats east of Cervantes (Figures 6 and 10).

Fresh groundwater is also found locally in swales in the Quindalup Dunes, as a thin layer above saline groundwater (Commander, 1994b).

Potential development and utilization

The superficial formations provide the most readily available source of groundwater to the region. Because of the commonly shallow depth and low salinity in one-third of the investigation area, there is overall good groundwater abstraction potential for public water supply, mining industry, agriculture and domestic irrigation. The volume of fresh groundwater (<1000 mg/L TDS) in storage within the superficial formations is about 1.52 x 10^9 m^3.

Groundwater from the Tamala Limestone is currently used for Cervantes, Jurien and partly for the Leeman – Green Head town water supply. Groundwater from the Tamala Limestone was also used for the Jurien mineral-sand treatment plant between 1975 and 1977 when the mine was operating. Throughout the coastal plain there is only a small number of farm bores, mostly for sheep and cattle use. Groundwater from the superficial formations is not used for commercial irrigation.

Yarragadee Formation

The Yarragadee Formation is a major aquifer in the northeast of the investigation area and contains large volumes of fresh groundwater in storage. It is a multilayered aquifer and part of an extensive regional groundwater-flow system. The aquifer is unconfined in the Arrowsmith Region and on the eastern part of the coastal plain where the superficial formations are unsaturated. Groundwater is confined in the Yarragadee Formation by shale and siltstone beds up to 10 m thick within the formation, and also by the overlying superficial formations on the western part of the coastal plain, which range in thickness from less than 5 m to over 30 m.

In the investigation area the Yarragadee Formation is mostly overlain by sand and clay of the Yoganup Formation and Guildford Formation. Groundwater flow in the Yarragadee Formation is mainly from the east where recharge occurs from infiltration of rainfall. Groundwater recharge has increased due to clearing for agriculture, and the watertable is rising at annual rates of up to 0.25 m (Commander, 1981). The direction of groundwater flow in the aquifer is predominantly to the west with some downward leakage from the overlying superficial formations in the Eneabba Plain (Figure 8).

The groundwater in the Yarragadee Formation is typically fresh to marginal with a salinity ranging from about 500 to 1500 mg/L TDS (Nidagal, 1995). Throughout more than half the investigation area, groundwater salinity in this formation is likely to be less than 1000 mg/L (Figures 6 and 12). North of the investigation area there is a marked increase in salinity from the intake area, along and to the east of the Gingin Scarp, to the discharge areas adjacent to the coast (Nidagal, 1995).

About 8 x 10^6 m^3 are abstracted annually for mineral-sand processing and for maintenance of water in a dredge pond at the Eneabba East mine south of Eneabba. Groundwater from the formation is also used for the Eneabba town water supply (100 x 10^3 m^3/year) and for stock use on farms. The groundwater resources in the Yarragadee Formation are large and virtually undeveloped in the Arrowsmith Region south and east of Eneabba.

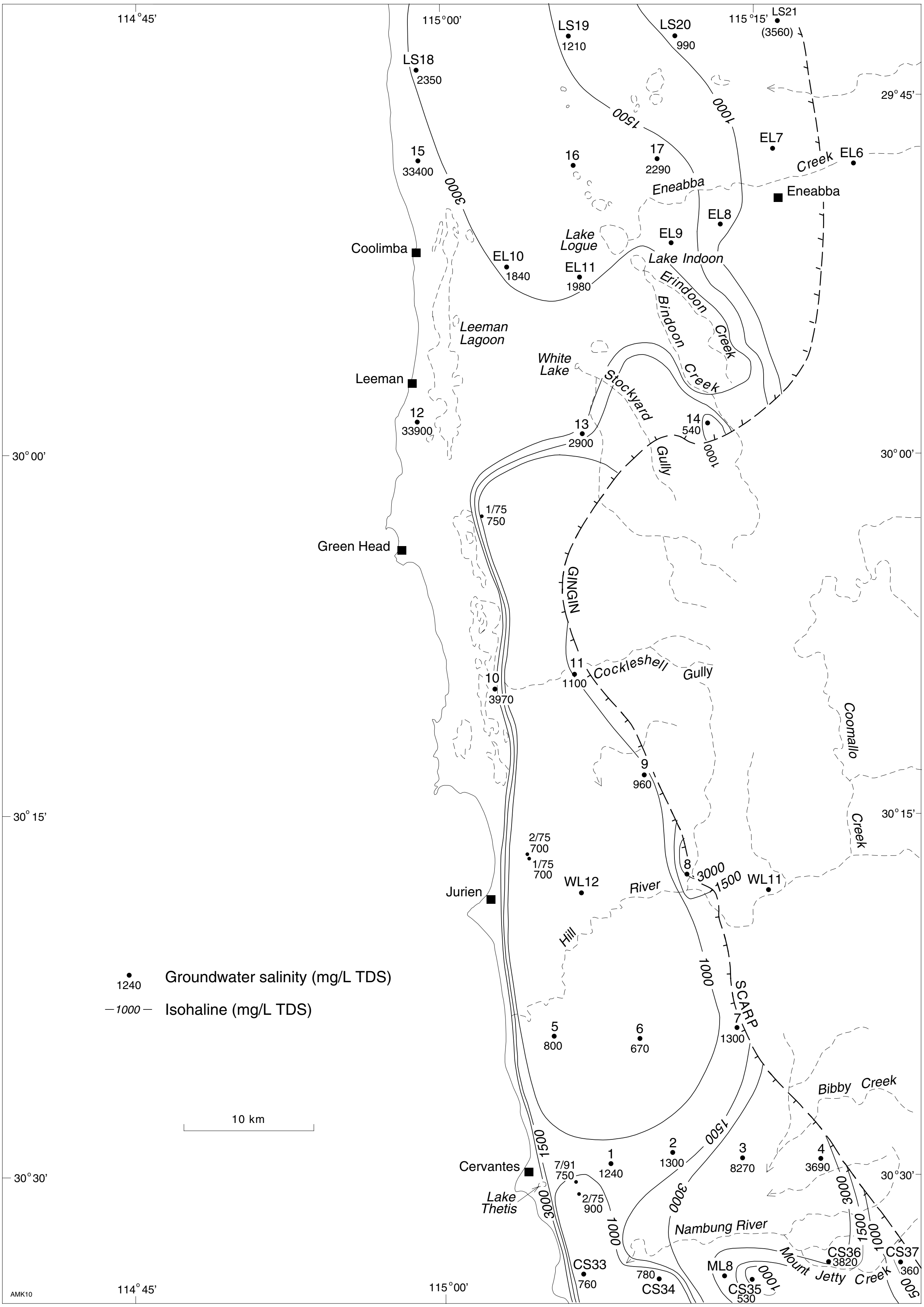

Figure 10. Groundwater salinity at the watertable

Cadda Formation

The Cadda Formation, with its relatively high content of shale and siltstone, small thickness, and narrow distribution, locally forms a minor multilayered aquifer in the area. Little is known of its hydrogeological characteristics. Exploratory drilling results indicate that there is upward groundwater flow from the underlying Cattamarra Coal Measures at site LS4 and to the overlying Tamala Limestone at site LS16. Groundwater is brackish at site LS17 with groundwater salinity decreasing with depth, from 2290 mg/L in bore LS17B to 1900 mg/L TDS in bore LS17A.

Cattamarra Coal Measures

The Cattamarra Coal Measures forms a multilayered confined aquifer consisting of interbedded siltstone, fine to coarse sandstone with carbonaceous and micaceous siltstone, and shale. Sandstone in the formation constitutes about 25%, which is substantially less than that in the Yarragadee Formation.

Groundwater in the Cattamarra Coal Measures is in limited hydraulic continuity with the groundwater in the overlying superficial formations, and to a lesser extent with that in the Yarragadee Formation. Aquifer recharge to the formation is from rainfall and surface runoff in outcrop areas and by downward leakage from the overlying Cadda and Yarragadee Formations. Recharge also takes place through the superficial formations west of Eneabba near EL8, where the hydraulic head decreases with depth (Commander, 1978).

Groundwater from the Cattamarra Coal Measures is probably discharged into the sea along the coastline above a saltwater interface north of Leeman. Significant discharge also occurs by upward leakage into the overlying Quaternary sediments. The aquifer also discharges to gaining streams, such as Bindoon and Erindoon Creeks on the Eneabba Plain. Groundwater also discharges from the formation in the low-lying area at the foot of the Gingin Scarp east of Cervantes where the potentiometric head of bores LS3A and LS4A is above ground level.

Groundwater is brackish to saline in the Cattamarra Coal Measures with salinities ranging from 1500 to 8270 mg/L TDS (Figures 6, 10 and 12). Groundwater may be fresh (<1000 mg/L TDS) in elevated areas of outcrop to the east of the investigation area, in the Arrowsmith Region.

Large volumes of groundwater (1.5 x 10^6 m^3/year) from the Cattamarra Coal Measures are used for mineral processing and to fill and maintain the waterlevel in a dredge pond at the Eneabba West mine. Groundwater is also used for farm water supplies southwest of Eneabba (Commander, 1994a).

Eneabba Formation

The Eneabba Formation is a major multilayered confined aquifer containing regional groundwater-flow systems. Groundwater in the Eneabba Formation is in hydraulic continuity with that in the Lesueur Sandstone. The sandstone beds are thicker in the Eneabba Formation, up to 100 m in EL9A, than in the overlying Cattamarra Coal Measures.

The Eneabba Formation is recharged by rainfall and surface runoff in outcrop areas. Local recharge also takes place from the overlying Cattamarra Coal Measures. In addition, recharge occurs from the sandy superficial formations just west of the Gingin Scarp near LS7, where the hydraulic head decreases with depth. At site LS 7 there is significant potential for downward groundwater-flow with a potentiometric head difference of 2.39 m over 41 m. Upward hydraulic gradients in EL9 and EL11 indicate that there is potential for upward groundwater flow from the Lesueur Sandstone into the basal sands of the Eneabba Formation.

Groundwater flow is northwestwards and southwestwards from a groundwater divide north of Cockleshell Gully. The Eneabba Formation aquifer discharges into the overlying superficial formations along the Beagle Fault east of Leeman. In the same area, at Three Springs, groundwater emerges from the Tamala Limestone and flows for a short distance before soaking back into the limestone (Commander, 1981). Some discharge also take place across geological boundaries and faults into the Lesueur Sandstone. Groundwater discharges at the coast north of Coolimba where at site LS15 there is potential for upward flow with a head difference between the deep and shallow bores of 0.19 m.

Groundwater in the Eneabba Formation is generally brackish (1000–3000 mg/L) except in bore LS14B where groundwater is fresh with a salinity of 540 mg/L TDS. The coastal saltwater interface was intersected at site LS15.

Large volumes of groundwater (up to 2 x 10^6 m^3/year) from the Eneabba Formation are used to irrigate clover and lucerne crops south of White Lake. Otherwise the large groundwater resources of mostly brackish groundwater in the Eneabba Formation are not utilised at present.

Lesueur Sandstone

The Lesueur Sandstone is a major aquifer containing large volumes of fresh groundwater in storage. It is mostly unconfined in the central part of the project area where it outcrops or is overlain by the Bassendean Sand and Tamala Limestone. Elsewhere the Lesueur Sandstone is confined by thick shale and siltstone beds of the overlying Jurassic units. The Lesueur Sandstone is hydraulically connected to the overlying Eneabba Formation.

Potentiometric surface configuration

The potentiometric heads measured in the Lesueur Sandstone during May 1993 are shown in Figure 11. A groundwater divide between northwestward and south-westward groundwater flow is north of Cockleshell Gully (Figure 11). The potentiometric head gradually declines from an elevation in excess of 80 m AHD at site LS9 at the foot of the Gingin Scarp to near sea level towards the coast in the vicinity of Cervantes. The groundwater flow is in a south-southwestly direction east of Jurien and swings in a more westerly direction in the Cervantes area where it discharges.

Recharge

Recharge to the Lesueur Sandstone is from rainfall and surface runoff east of the Gingin Scarp, and in particular from the Hill River, where the formation is exposed. Recharge also occurs by infiltration through the superficial formations along the eastern edge of the coastal plain (Figure 8). Some groundwater flow into the Lesueur Sandstone from the Eneabba Formation and Cattamarra Coal Measures takes place across faults. The high groundwater salinity (1850 mg/L TDS) in the Lesueur Sandstone in bore LS2A implies that the flow of brackish water from the Eneabba Formation must be significant compared with direct recharge.

The recharge to the Lesueur Sandstone can be estimated by summing up that from direct rainfall in outcrop areas (133 km^2), which includes areas of outcrop of the Eneabba Formation as the latter is in hydraulic connection with the underlying Lesueur Sandstone, plus the recharge from downward leakage from the overlying superficial formations (102 km^2). Using an average rainfall recharge rate of 5% and a recharge rate of 2.5% for downward leakage, this gives an annual recharge of approximately 5.5 x 10^6 m^3. Additional recharge also takes place from the Hill River and westward flow from younger Mesozoic formations.

Throughflow

The southwestward groundwater flow through the Lesueur Sandstone along the 20 m potentiometric contour in the Cervantes–Jurien area can be assessed by using the Darcy equation. By taking into account a hydraulic conductivity of 15 m/day, an aquifer thickness of 600 m, a hydraulic gradient of about 3 x 10^{-3}, and the aquifer width of 28 km, the southwestward flow is 756 x 10^3 m^3/day or 276 x 10^6 m^3/year. This amount is very large in comparison with the recharge estimate. It is likely that the calculation of throughflow is not appropriate in this case, and the hydraulic gradient may reflect a lack of hydraulic continuity in the aquifer.

Discharge

The southwesterly direction of groundwater movement in the Lesueur Sandstone indicates that the groundwater is discharged along the Beagle Fault system, which forms the eastern boundary of the impermeable Kockatea Shale. In the coastal area there is substantial upward ground-water discharge into the overlying Woodada Formation where it is present, otherwise into the highly transmissive Tamala Limestone, where the watertable is lower than the potentiometric head in the Lesueur Sandstone (Figures 8 and 11). Harley (1975) noted that the potentiometric levels appear to increase with depth, and these levels are higher than that in the overlying Tamala Limestone, indicating upward leakage.

Groundwater flow into the Lesueur Sandstone west of the Beagle Fault system will eventually discharge to the sea through the Tamala Limestone. Some discharge probably takes place across the Beagle Fault system where the Quaternary unconformity has been cut below the watertable in the Lesueur Sandstone, allowing an overflow into the Tamala Limestone. This appears to take place at Cockleshell Gully where the watertable in a nearby shallow bore is higher than in Woolmulla Pool, which is situated just west of the Beagle Fault system and possibly is based on impermeable Kockatea Shale (Commander, 1981).

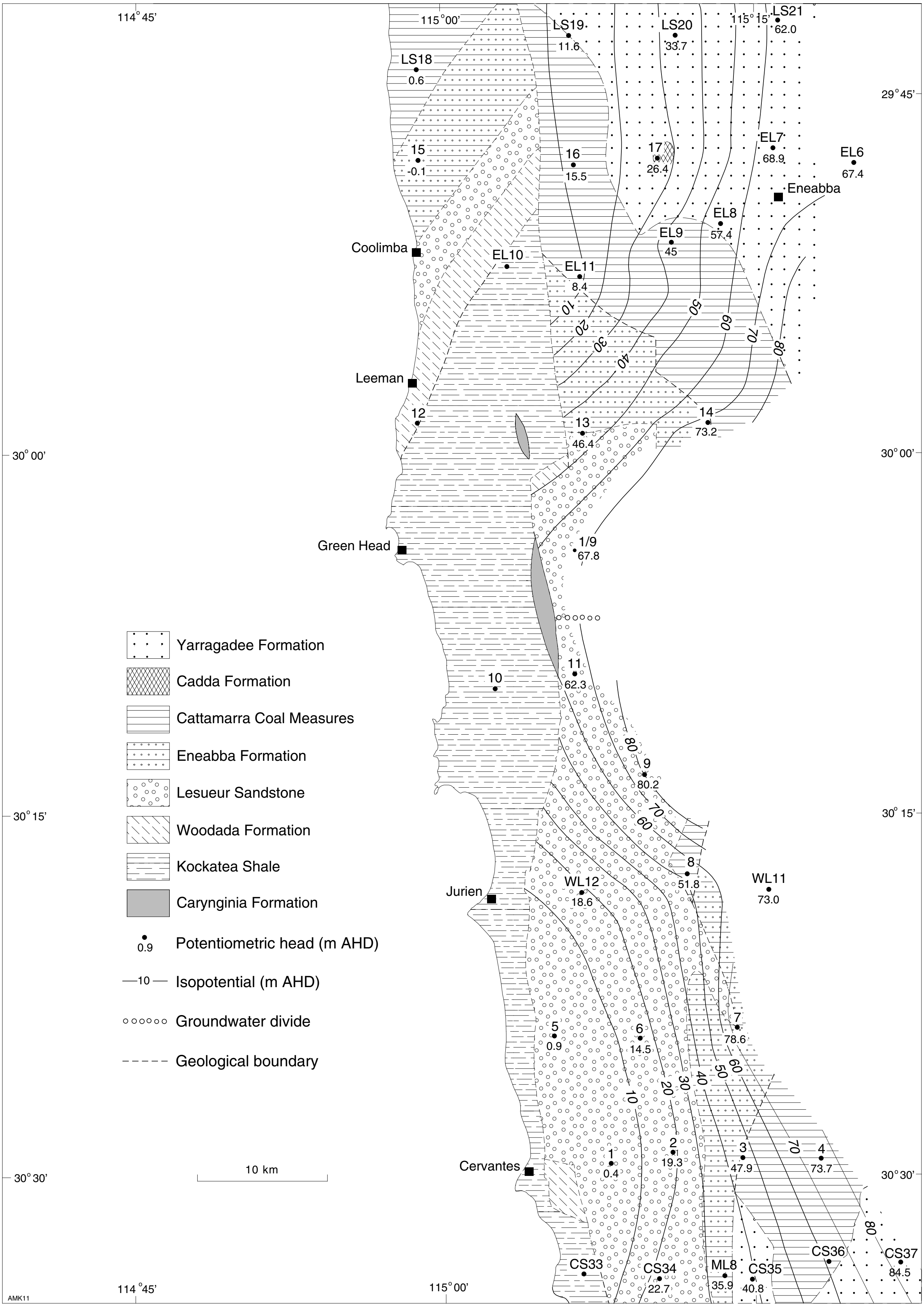

Figure 11. Isopotentials in the top of the Mesozoic formations beneath the coastal plain

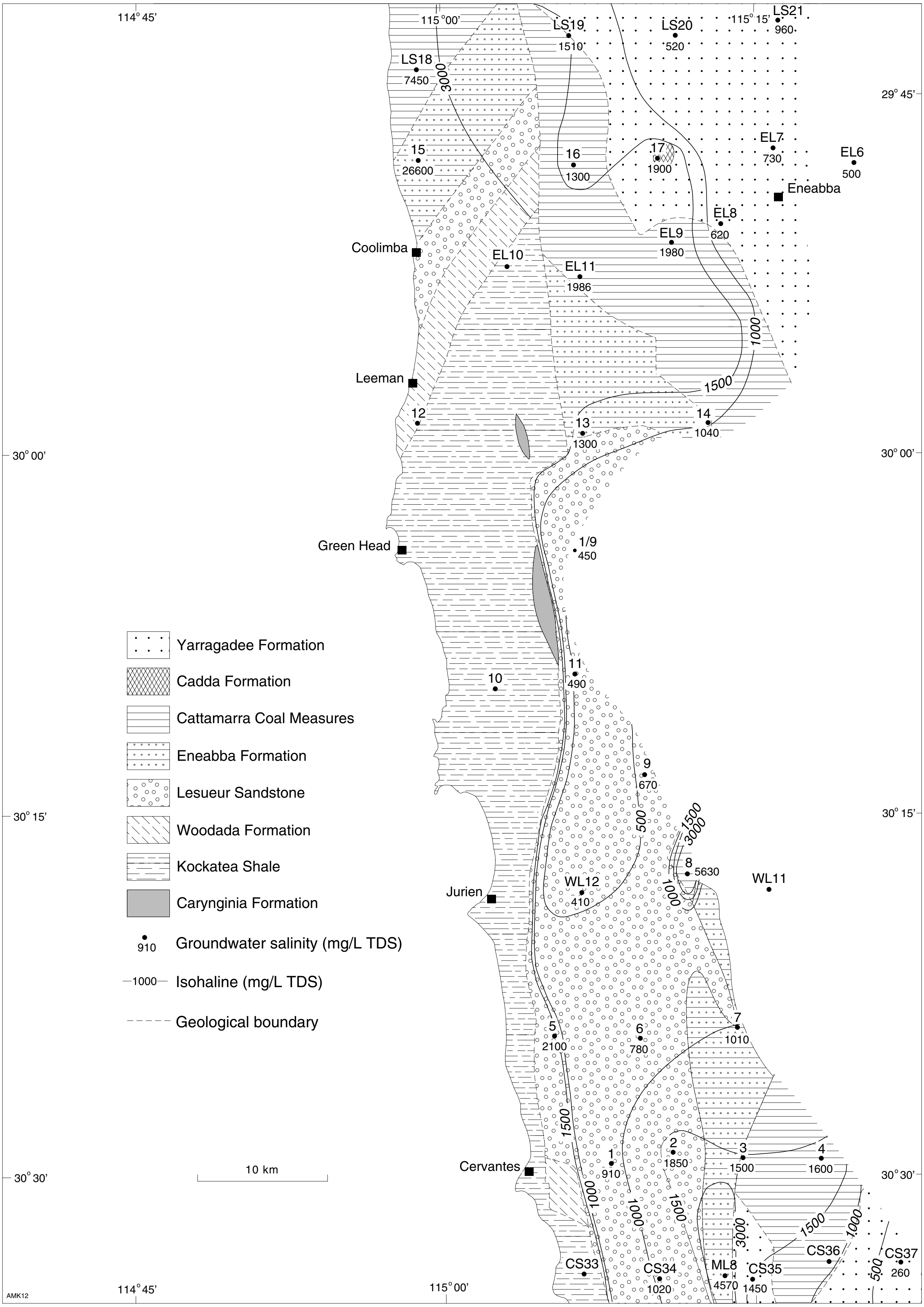

Figure 12. Groundwater salinity in the top of the Mesozoic formations beneath the coastal plain

Groundwater discharge from the formation maintains Canover Pool in the Hill River. Subsurface discharge may also take place elsewhere along the Beagle fault system and may have been a factor in the formation of caves 10 km northeast of Jurien (Commander, 1981).

Salinity

The groundwater in the Lesueur Sandstone is typically fresh to marginal with a salinity ranging from about 500 mg/L in bore LS11A to 2100 mg/L TDS in bore LS5A near the coast. Throughout most of the investigation area, groundwater salinity in this formation is less than 1000 mg/L (Figures 6 and 12). There is a marked increase in salinity from the intake area, on the Gingin Scarp, to the discharge areas adjacent to the coast, where it exceeds 2000 mg/L. There appears to be significant leakage of brackish groundwater into the Lesueur Sandstone from the Eneabba Formation and Cattamarra Coal Measures across faults east of Cervantes.

Potential development and utilisation

The Lesueur Sandstone contains large resources of fresh groundwater with a salinity of less than 1000 mg/L. Present use of the Lesueur Sandstone is limited to the Leeman – Green Head town water supply (about 200 x 103 m3/year), and there is significant potential for further development. Bore yields of 500–1000 m^3/d are anticipated in the Cervantes and Jurien areas. Groundwater from the Lesueur Sandstone was formerly used for processing mineral sands from the Jurien deposit.

Airlift yields in exploratory bores were low (<50 m^3/d) in the southern part of the investigation area despite the high porosity of the Lesueur Sandstone. This is partially due to the narrow bore diameter (50 mm ID) and poor bore development. Bores at the Jurien minesite, south of Hill River, are capable of yielding up to 1800 m^3/d (for a screen length of 250 m). In the central area, bores LS9B, LS11B and WL12 (80 mm ID) produced an airlift flow rate of 160, 187 and 195 m^3/d, respectively. Further north, Green Head 1/91 bore (210 mm ID) was test pumped at 2000 m^3/d and is capable of producing up to 3000 m^3/d (Kern, 1993b). Although the increase in yields may be due to a greater casing size and bore development, it is possible that the permeability of the formation is higher in the north.

Woodada Formation

The Woodada Formation forms a minor multilayered aquifer with confining argillaceous beds, hydraulically connected to the overlying Lesueur Sandstone. The Woodada Formation was not tested during the drilling investigation; however, there is information from Watheroo Line 12 screened at a depth of 712-718 m (Harley, 1975).

The groundwater salinity in the Woodada Formation in WL12 is low, about 700 mg/L TDS, but groundwater salinity is likely to be higher elsewhere where the formation comprises thicker beds of fine-grained sandstone and siltstone.

Although the yield by air-lifting was relatively good in WL12, the resistivity logs of the bore suggest a relatively low permeability.

Kockatea Shale

Owing to the high content of shale and siltstone, the Kockatea Shale forms an aquiclude and acts as a barrier to westerly groundwater flow. Any groundwater that may be present in thin sandstone beds is likely to be saline due to the low permeability of the formation and the proximity of the Indian Ocean. The formation groundwater salinity is reported to be 49 000 mg/L in Jurien Bay 1 water bore (Milbourne, 1967).

Permian formations

There is very little information on groundwater in the Permian formations in the investigation area. Brackish groundwater (3000 mg/L) occurs at a depth of 490 m in the Irwin River Coal Measures in Amax Green Head 1 coal exploratory bore (Romanoff and Shepperd, 1974), but this is probably derived from limited local circulation within the Lesueur Sandstone aquifer east of the Beagle Fault system (Commander, 1981). Otherwise, the near surface Permian formations are predominantly shale.

Hydrochemistry

Chemical analyses of groundwater are shown in Table 2 and the concentrations of the major ions expressed as a percentage of the total milliequivalents per litre are plotted on a Piper trilinear diagram (Figure 13). The groundwater from all the bores can be classified as sodium chloride type. The chemical compositions of the groundwater in the superficial formations and the underlying Mesozoic aquifers are similar, indicating a close hydraulic connection between the aquifers.

Nitrate concentrations are generally less than 1 mg/L (as NO_3^-); however, the relatively low-salinity groundwater in the Eneabba Formation in the shallow bore at LS14 contained 34 mg/L.

The pH measured in the laboratory ranged from 6.7 to 8.2. Silica concentrations varied between 3 and 85 mg/L, with those concentrations in excess of 50 mg/L being recorded from the bores located towards the Gingin Scarp. Boron and fluoride concentrations are each generally less than 1 mg/L with the exception of bores LS12A, LS15A and LS15B where the boron concentrations are 4.2, 3.3 and 3.4 mg/L respectively. There is also a relatively high concentration of fluoride (1.3 mg/L) in bores LS8A and LS8B.

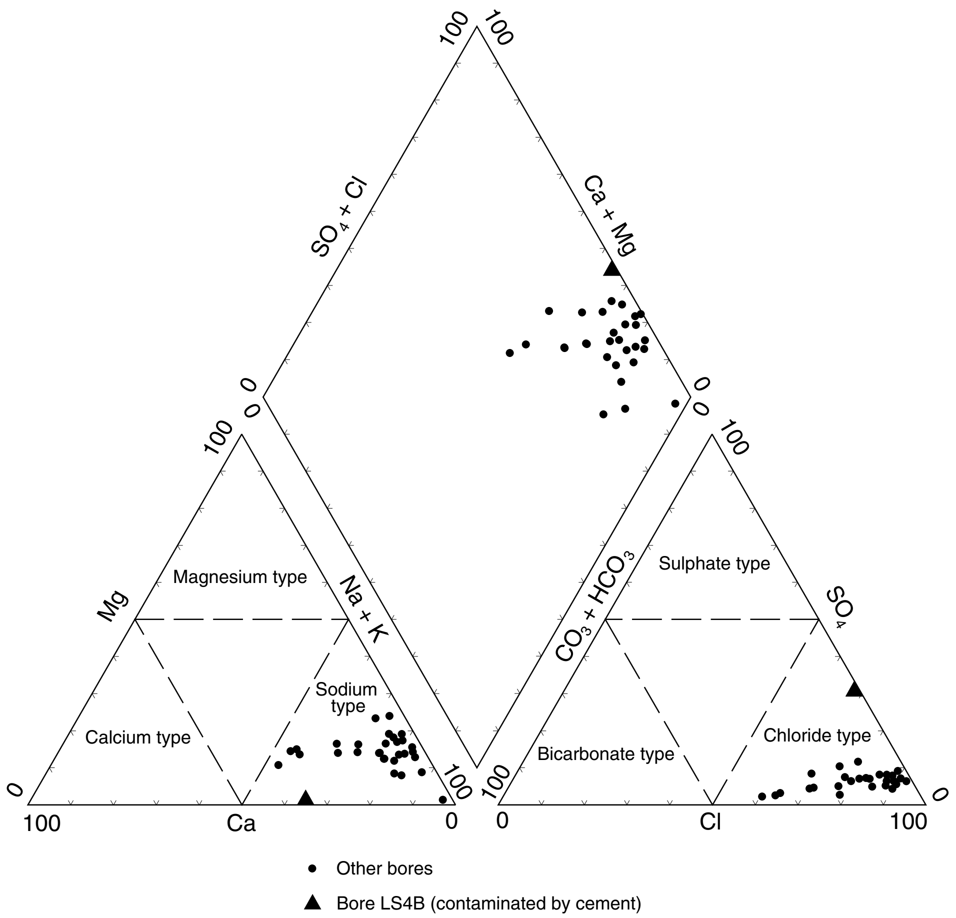

Figure 13. Piper trilinear diagram

Conclusions

The Leeman shallow-drilling project has provided new data on the hydrogeology of the coastal plain north of Cervantes, in the northern Perth Basin.

The groundwater in the unconfined superficial formations is fresh to brackish. The highest salinities were recorded in bores located in the lower catchment of the Nambung River and in the northern part of the project area, between Eneabba and the coast. The Lesueur Sandstone constitutes a major freshwater aquifer in the southern half of the project area. The Yarragadee Formation forms locally a major multilayered confined aquifer containing fresh to brackish groundwater. The Eneabba Formation forms minor multilayered confined aquifer systems with groundwater salinities ranging from fresh to saline. The relatively thinner sandstone beds in the Cattamarra Coal Measures contain mainly brackish to saline groundwater.

The superficial formations and the Mesozoic formations discharge large volumes of groundwater to the sea. Much of this discharge may flow through karstic solution channels in the Tamala Limestone.

Groundwater storage in the superficial formations is estimated to be 5.6 x 10^9 m^3, of which 1.5 x 10^9 m^3 is fresh groundwater, and the total throughflow is about 82.8 x 10^6 m^3/year. Significant groundwater resources occur in the Lesueur Sandstone and Yarragadee Formation. Groundwater is mostly brackish in the Eneabba Formation whereas the Cattamarra Coal Measures contains brackish to saline groundwater.

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