# Hydrogeology of the Collie Basin, Western Australia

by
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## Abstract

The Collie Basin, in the southwest of Western Australia, contains important fresh groundwater resources. An exploratory drilling program has provided new information on the hydrogeology of the area. The basin comprises two grabens, the Premier and Cardiff Sub-basins, which are separated by a basement high. The geology of the basin is reviewed, with particular emphasis on the contribution of the drilling in the areas of stratigraphy and structure.

The hydrogeology of the Collie Basin is complex and reflects the complicated geological environment. The basin contains a regional groundwater flow system in the Collie Coal Measures. Groundwater flow is generally from the margin of the Cardiff Sub-basin, and from a groundwater mound in the northern Premier Sub-basin, towards the Collie River where discharge occurs. The groundwater is unconfined in the upper part and confined at depth. There are about 7300 x $10^6$ $m^3$ of groundwater in storage for most of which the salinity is lower than 750 mg/L (total dissolved solids). Annual recharge is estimated to be 31 x $10^6$ $m^3$, of which about 26 x $10^6$ $m^3$ is rainfall recharge (13% of average annual rainfall) and some 5 x $10^6$ $m^3$ is from streams. Groundwater abstraction at mines and from production borefields exceeds estimated annual recharge by about 25%. This has led to mining of the groundwater resources. Consequently, the watertable has been depressed over about 100 $km^2$ of the basin with groundwater heads at depth having been modified over an even greater area, and possibly to the boundary of the basin.

**KEYWORDS:** Collie Basin, hydrogeology, geology, groundwater, groundwater resources

## Introduction

The Collie Basin, which lies about 160 km south-southeast of Perth in the southwest of Western Australia (Fig. 1), contains the State's only producing coal mines. These provide fuel for the generation of about 70% of the electricity which is consumed in the southwest of the State. There are seven operating mines in the basin; the Muja and Chicken Creek opencut mines operated by The Griffin Coal Mining Company, and Western Collieries' WO3 and WO5 opencut mines and WD2, WD6, and WD7 underground mines (Fig. 2).

The basin contains substantial resources of fresh groundwater in an area where the groundwater is typically brackish to saline and in small supply. These resources are important for both coal mining and power generation: control of groundwater inflows to both opencut and underground mines is essential to ensure safe and efficient operation, and groundwater from the basin is used for cooling at the nearby Muja Power Station. Despite the importance of groundwater, investigations to date have focused on the various mine groundwater-control schemes and power station water supplies. There has been no systematic investigation to provide a regional understanding of the basin hydrogeology.

In 1986 the Geological Survey of Western Australia (GSWA) proposed a drilling and testing program aimed at improving the knowledge of the hydrogeology of the basin to allow better assessment and management of the groundwater resources (Moncrieff, 1986). The need for this work was emphasized in a major report on landuse planning in the basin (Collie Land Use Working Group, 1987) and in a draft water resources management strategy for the basin (Water Authority of Western Australia, 1988). It was intended that the investigation program be conducted in two phases. The current study was designed to define the configuration of the watertable, identify groundwater recharge and discharge areas and the directions of shallow groundwater flow, and to provide a network of bores for monitoring watertable fluctuations. It is recognized that the deeper aquifers have been highly disturbed due to groundwater abstraction and, in subsequent work, the hydrogeology of the deeper parts of the basin will be investigated. Phase 1 of the investigation program was undertaken during 1989 and the scope, data analysis and conclusions form the subject of this paper.

### Location and topography

The Collie Basin, which lies some 50 km east of Bunbury (Fig. 1), is about 27 km long, up to 13 km wide, and has an area of approximately 225 $km^2$. The town of Collie is situated on the northern margin of the basin.

The basin lies within a northwesterly trending valley in the Darling Plateau. The land surface slopes towards the northwest from about 250 m Australian Height Datum (AHD) at the southern extremity of the basin to about 160 m AHD at the northern end near the upstream part of the Wellington Reservoir. Hills on the Darling Plateau

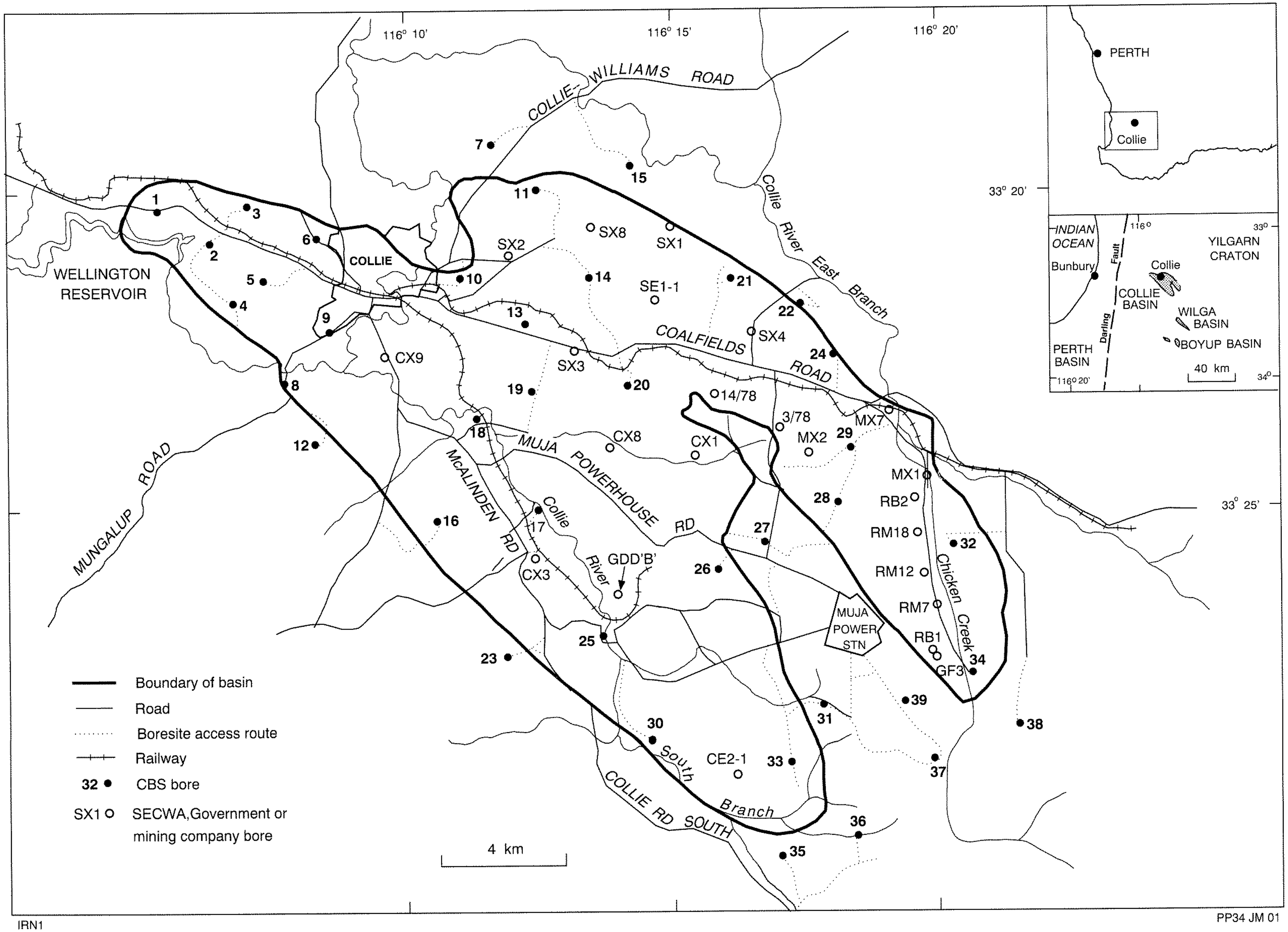


**Figure 1. Location**

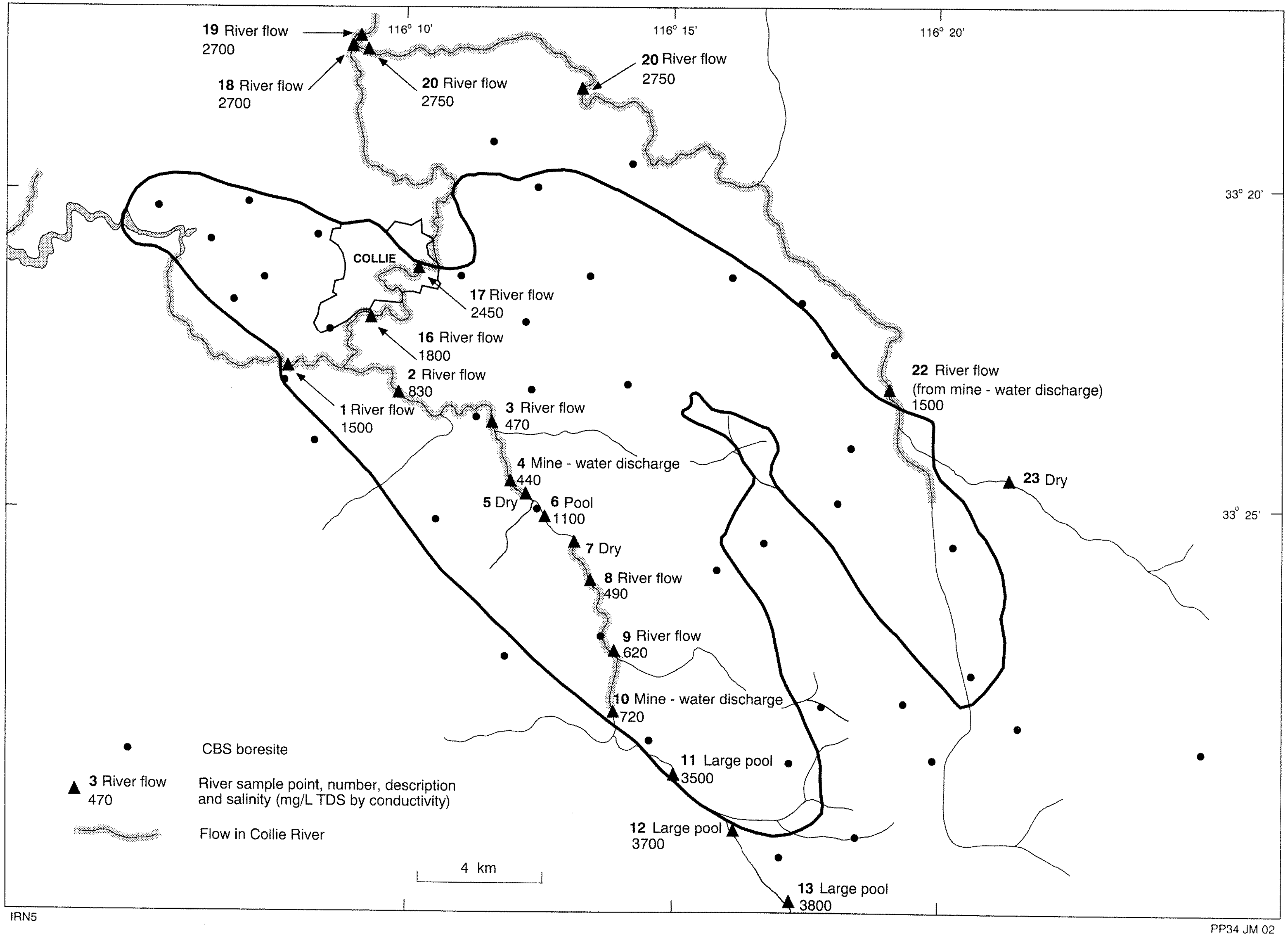


**Figure 2. River sampling, April 1990**

to either side and north of the basin reach an elevation of about 350 m AHD. In places there is a decrease of elevation across the basin margin into the basin.

## Drainage

The area is drained by two major tributaries of the Collie River; the Collie River East Branch and the Collie River South Branch (hereafter referred to as the East Branch and the South Branch), which flow northwest towards the Wellington Reservoir. The stream valleys inside the basin are broad and shallow whereas outside they are generally steep sided and controlled by structure in the Yilgarn Craton. Wetlands occur in the source areas of many of the tributaries which rise inside the basin.

Water pumped from operating mines is discharged at several places to the South Branch and also to Chicken Creek, a tributary of the East Branch. Power station blowdown water is also discharged to the Collie River system via Chicken Creek.

Flow in the East Branch ceases east of the Collie Basin during summer, but is maintained downstream from near the eastern margin of the basin (Fig. 3) by water discharged from the Chicken Creek mine. Flow in the South Branch also ceases south of the basin during summer. However, it is maintained inside the basin by discharge of mine water at several locations in an 8 km-long section near the WO5 opencut mine, between some 500 m south of sampling point 7 and sampling point 10 (Fig. 3). Flow in the South Branch is permanent downstream of where mine water is discharged to the river between sampling points 4 and 5. Permanent pools, which are maintained by groundwater discharge, remain in the river bed when there is no flow. River flow recommences in these sections after the first major winter rain, but may cease again if the rainfall does not persist.

River water in flowing sections of the South Branch had a salinity of about 450–830 milligrams per litre total dissolved solids (mg/L TDS) during April 1990, but the water from some of the pools had a higher salinity, from 1100–6700 mg/L (Fig. 3). The salinity of the water in the East Branch at that time ranged from 1500–3000 mg/L, and downstream of the confluence of the two branches it was about 1500–1800 mg/L.

## Climate

The Collie area has a Mediterranean climate with hot, dry summers and cool, wet winters. Annual rainfall averages around 1100 mm in the extreme northwest and decreases to 742 mm at the Muja Power Station in the southeast. About 75% of the rain falls in the five months from May to September, and the average annual potential evaporation at Collie is 1650 mm.

## Previous work

The first detailed geological investigation of the area was undertaken by Lord (1952). Accounts of the general geology are also given by Low (1958), Lowry (1976), Wilde (1981), Wilde and Walker (1982), Park (1982), Kristensen and Wilson (1986), and Wilson (1990). Recent work by the Geological Survey on various aspects of the geology is described by Backhouse and Wilson (1989), Wilson (1989), and Davy and Wilson (1989). An extensive review of the geology of the basin is currently being undertaken (Le Blanc Smith,1993).

Numerous unpublished hydrogeological reports have been prepared by consultants for the State Energy Commission of Western Australia (SECWA) and mining companies including, since 1986, biennial reviews of the groundwater-level monitoring that is undertaken in the basin for SECWA. Descriptions of the hydrogeology and groundwater resources of the basin have been prepared by Hirschberg (1976), Moncrieff (1985) and Allen (1991). Groundwater-control schemes at some of the mines are described by Vogwill and Brunner (1985), Humphries and Hebblewhite (1988), Hammond and Boyd (1988), and Dundon et al. (1988).

## Investigation program

Forty-seven bores were constructed from June to September 1989 at 39 sites on a 3 km grid which follows the long axis of the basin (Fig. 1). Bores were sited to augment the existing SECWA monitoring bore network and to avoid opencut mines. Eleven sites lie outside the accepted limit of the Collie Coal Measures and three sites are alongside wetlands (CBS14, CBS21 and CBS27). The bores are identified by the prefix 'CBS' (Collie Basin Shallow) followed by the site number. At sites where multiple bores were drilled an alphabetical suffix (commencing with 'A') is added to the bore identifier.

A watertable-monitoring bore, with a 5–12 m slotted interval beginning at a nominal depth of 5 m below the watertable, was drilled at each site. At six sites (CBS2, CBS9, CBS14, CBS17, CBS21 and CBS25), an additional bore was constructed to allow monitoring of an interval about 50 m below the surface. The slotted interval in these bores is 3.5–8 m long. At site CBS14 a third monitoring bore, of intermediate depth, was also constructed. CBS18 was drilled alongside an existing monitoring bore (PWD5/80) that is open at 26–32 m depth (about 25 m below the watertable). An additional bore was drilled to 347 m at site CBS5 to investigate the stratigraphy in the area and to provide groundwater information from a deep interval in the northwestern part of the basin.

The watertable-monitoring bores, other than CBS5B and the intermediate bore at site CBS14, were drilled by a contractor using the reverse circulation (RC) air-core method. The other bores were drilled by the Department of Mines Drilling Branch using the wireline-core method, except at site CBS5 where the mud-rotary method was used.

Lithological samples were taken over 1 m intervals during the RC drilling, and 3 m intervals during the mud-rotary drilling. These samples and core from the other bores are stored in the GSWA core library. Palynological

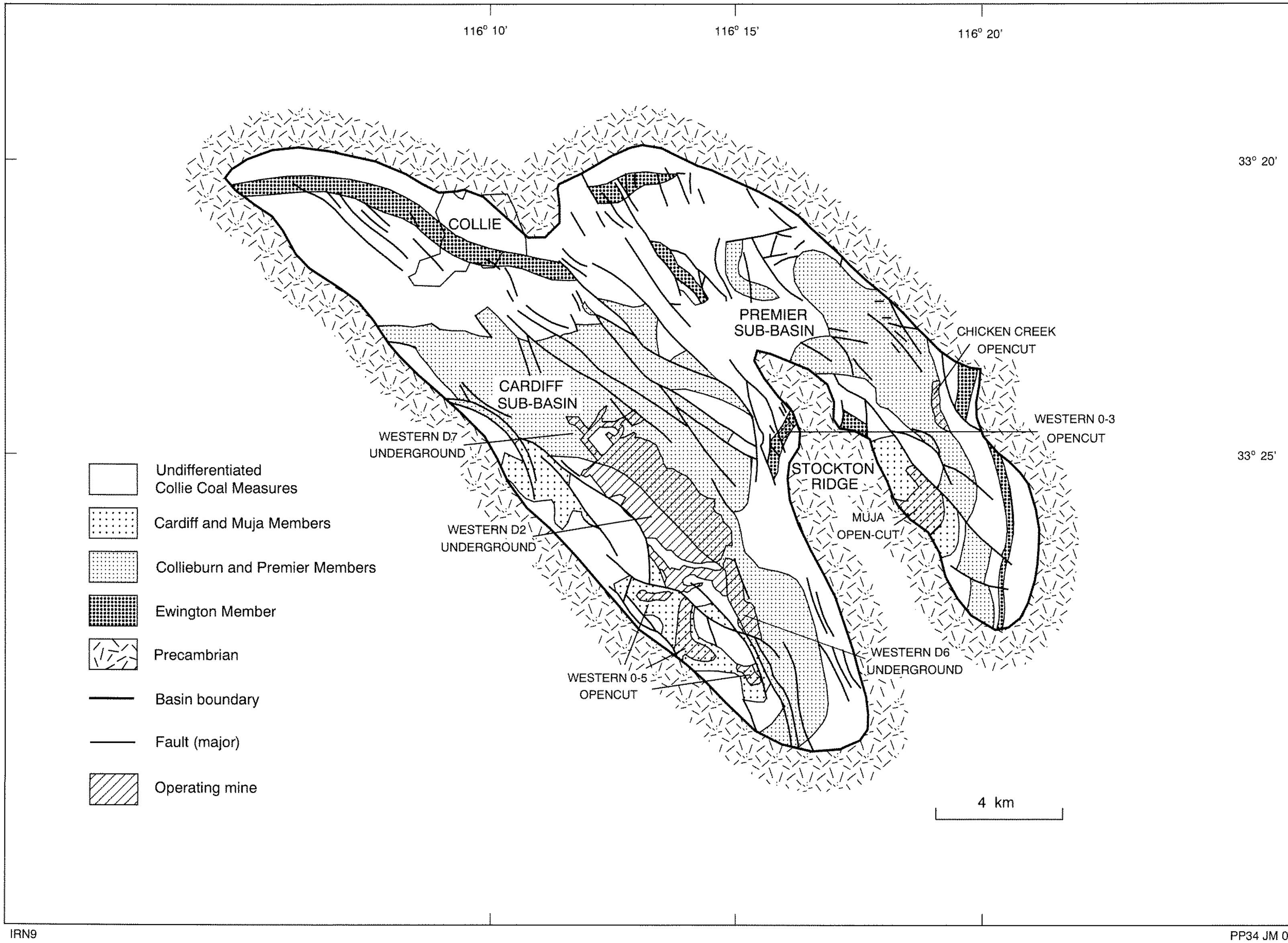


**Figure 3. Pre-Cretaceous geology showing subcrop of faults, coal members and operating mines (modified after Wilson, 1990; Le Blanc Smith, 1990)**

## Table 1. Summary of bore data

| Bore | AMG Zone 50 | | Construction | | Total depth (m bns) | Elevation | | Slotted interval (m bns) | Potentiometric head (m AHD) (c) | Salinity TDS (mg/L) | Airlift yield ($m^3$/day) | Status of bore |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Easting | Northing | Commenced | Completed | | Concrete pad (m AHD) | Top of casing (m AHD) | | | | | |
| CBS1 | 414 930 | 6 310 710 | 28.06.89 | 28.06.89 | 21 | 187.127 | 187.714 | 14.5 – 20.5 | 180.619 | 1 350 | 2 | obs. |
| CBS2A | 416 480 | 6 309 750 | 29.06.89 | 29.06.89 | 12 | 176.802 | 177.570 | 5 – 11 | 173.247 | 40 | 6.2 | obs. |
| CBS2B | 416 480 | 6 309 750 | 22.08.89 | 22.08.89 | 45 | 176.581 | 177.452 | 39 – 45 | 171.577 | 110 | 6.2 | obs. |
| CBS3 | 417 670 | 6 310 850 | 30.06.89 | 30.06.89 | 23 | 194.614 | 195.407 | 16 – 22.5 | 188.482 | 500 | (e) - | obs. |
| CBS4 | 417 150 | 6 308 010 | 05.08.89 | 08.07.89 | 57 | 222.603 | 223.415 | 42 – 54 | 179.245 | 240 | (e) - | obs. |
| CBS5A | 418 080 | 6 308 680 | 13.09.89 | 21.09.89 | 347 | 229.902 | 230.528 | 305 – 311 | 190.213 | 220 | 19.2 | obs. |
| CBS5B | 418 080 | 6 308 680 | 21.09.89 | 25.09.89 | 67 | 229.880 | 230.785 | (b) ?45 – 52.7 | 178.907 | (d) 380 | (e) - | obs. |
| CBS6 | 419 540 | 6 310 050 | 01.07.89 | 01.07.89 | 21 | 205.689 | 206.198 | 8 – 17 | 199.358 | 740 | 2.3 | obs. |
| CBS7 | 424 870 | 6 312 560 | 01.07.89 | 01.07.89 | 13 | 215.840 | 216.618 | 7 – 13 | 214.718 | 1 160 | 14.4 | obs. |
| CBS8 | 418 680 | 6 305 600 | 04.07.89 | 04.07.89 | 11 | 186.665 | 187.310 | 4 – 10 | 183.980 | 300 | 2.9 | obs. |
| CBS9A | 419 950 | 6 307 160 | 04.07.89 | 04.07.89 | 15 | 187.435 | 188.168 | 7 – 13 | 182.958 | 130 | 3.9 | obs. |
| CBS9B | 419 950 | 6 307 160 | 15.08.89 | 16.08.89 | 57 | 187.159 | 188.058 | 48 – 54 | 180.663 | 560 | 5.1 | obs. |
| CBS10 | 423 920 | 6 308 910 | 04.07.89 | 04.07.89 | 15 | 201.448 | 202.138 | 9 – 15 | 200.158 | 7 150 | (e) - | obs. |
| BS11 | 426 180 | 6 311 300 | 09.08.89 | 10.08.89 | 24 | 225.107 | 225.943 | 10 – 16 | 214.453 | 1 990 | (e) - | obs. |
| CBS12 | 419 730 | 6 304 040 | 30.07.89 | 01.09.89 | 19 | 222.066 | 223.002 | 11 – 19 | 210.269 | 690 | 1.6 | obs. |
| CBS13 | 425 810 | 6 307 510 | 11.07.89 | 11.07.89 | 15 | 213.337 | 214.271 | 6 – 15 | 204.321 | 1 950 | (e) - | obs. |
| CBS14A | 427 662 | 6 308 724 (a) | 11.07.89 | 12.07.89 | 9 | 212.744 | 213.670 | 1 – 7 | 211.832 | 80 | 5.8 | obs. |
| CBS14B | 427 661 | 6 308 726 (a) | 12.07.89 | 13.07.89 | 21 | 212.907 | 213.704 | 14 – 20 | 211.294 | 70 | 6.6 | obs. |
| CBS14C | 427 656 | 6 308 729 (a) | 17.08.89 | 21.08.89 | 54 | 213.147 | 214.036 | 32 – 35.5 | 210.098 | 170 | 6.2 | obs. |
| CBS15 | 428 820 | 6 312 150 | 10.08.89 | 10.08.89 | 9 | 206.217 | 206.937 | 0 – 6 | 204.439 | 580 | 3.2 | obs. |
| CBS16 | 423 160 | 6 301 640 | 18.07.89 | 18.07.89 | 21 | 212.305 | 213.267 | 12 – 21 | 199.479 | 280 | 2.9 | obs. |
| CBS17A | 426 230 | 6 302 060 | 10.07.89 | 10.07.89 | 12 | 183.124 | 183.871 | 3 – 10.5 | 175.993 | 600 | 0.6 | obs. |
| CBS17B | 426 230 | 6 302 060 | 29.08.89 | 30.08.89 | 48 | 183.163 | 184.118 | 39 – 45 | 164.343 | 1 100 | 3.3 | obs. |
| CBS18 | 424 410 | 6 304 560 | 14.07.89 | 14.07.89 | 9 | 182.674 | 183.527 | 3 – 9 | 181.167 | 70 | 14.4 | obs. |
| CBS19 | 425 960 | 6 305 300 | 17.07.89 | 17.07.89 | 36 | 217.654 | 218.569 | 24.5 – 33.5 | 190.664 | 290 | 5.4 | obs. |
| CBS20 | 428 920 | 6 305 720 | 13.07.89 | 14.07.89 | 25 | damaged | 213.511 | 18 – 24 | 195.491 | 680 | 3.3 | obs. |
| CBS21A | 431 625 | 6 308 500 | 11.07.89 | 11.07.89 | 9 | 211.102 | 211.975 | 0 – 5 | 210.468 | 70 | 8.6 | obs. |
| CBS21B | 431 690 | 6 308 520 | 23.08.89 | 24.08.89 | 42 | - | - | - | - | - | - | abd |
| CBS21C | 431 690 | 6 308 520 | 24.08.89 | 25.08.89 | 51 | - | - | - | - | - | - | abd |
| CBS21D | 431 690 | 6 308 520 | 28.08.89 | 28.08.89 | 49 | 211.810 | 212.754 | 43 – 49 | 202.476 | 210 | 7.8 | obs. |
| CBS22 | 433 800 | 6 307 850 | 08.08.89 | 09.08.89 | 15 | - | | | - | - | - | abd |
| CBS23 | 425 280 | 6 297 680 | 18.07.89 | 19.07.89 | 15 | 223.729 | 224.481 | 6 – 15 | 220.716 | 390 | (e) - | obs. |
| CBS24 | 434 940 | 6 306 460 | 07.08.89 | 08.08.89 | 42 | 233.625 | 234.509 | 28 – 35 | 205.319 | 450 | 1.7 | obs. |
| CBS25A | 428 120 | 6 298 260 | 09.07.89 | 09.07.89 | 9 | 186.360 | 187.331 | 1 – 7 | 183.241 | 1 110 | 10.8 | obs. |
| CBS25B | 428 120 | 6 298 260 | 31.08.89 | 31.08.89 | 48 | 186.607 | 187.501 | 39 – 45 | 81.073 | 210 | 7.2 | obs. |
| CBS26 | 431 300 | 6 300 190 | 30.07.89 | 01.08.89 | 63 | 238.448 | 239.332 | 50 – 62 | 191.147 | 390 | 6.2 | obs. |
| CBS27 | 432 660 | 6 300 940 | 10.07.89 | 10.07.89 | 10 | 216.830 | 217.565 | 0 – 6 | 215.835 | 490 | 1.7 | obs. |
| CBS28 | 434 910 | 6 302 180 | 02.08.89 | 04.08.89 | 66 | 255.093 | 256.084 | 60 – 66 | 189.604 | 1 310 | (e) - | obs. |
| BS29 | 435 300 | 6 303 690 | 04.08.89 | 05.08.89 | 45 | 240.303 | 241.206 | 33 – 45 | 206.298 | 370 | 2.3 | obs. |
| CBS30 | 429 480 | 6 295 340 | 28.07.89 | 28.07.89 | 30 | 211.693 | 212.580 | 21 – 29 | 190.245 | 1 000 | 3.2 | obs. |
| CBS31 | 434 580 | 6 296 110 | 21.07.89 | 21.07.89 | 12 | 230.222 | 231.177 | 5 – 11 | 224.469 | 2 280 | 6.6 | obs. |
| CBS32 | 438 450 | 6 300 960 | 06.08.89 | 06.08.89 | 9 | 219.723 | 220.573 | 1 – 9 | 214.723 | 110 | 2.2 | obs. |

**Table 1. (*continued*)**

| Bore | AMG Zone 50 | | Construction | | Total depth (m bns) | Elevation | | Slotted interval (m bns) | Potentiometric head (m AHD) (c) | Salinity TDS (mg/L) | Airlift yield ($m^3$/day) | Status of bore |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Easting | Northing | Commenced | Completed | | Concrete pad (m AHD) | Top of casing (m AHD) | | | | | |
| CBS33 | 433 570 | 6 294 580 | 25.07.89 | 06.08.89 | 63 | 235.654 | 236.540 | 51 - 63 | 183.245 | 730 | 1.0 | obs. |
| CBS34 | 438 880 | 6 297 080 | 06.08.89 | 06.08.89 | 9 | 223.269 | 224.069 | 1 - 8 | 221.549 | 70 | 7.2 | obs. |
| CBS35 | 433 000 | 6 291 640 | 18.07.89 | 18.07.89 | 12 | 197.629 | 198.594 | 2 - 10 | 195.086 | 70 | 4.8 | obs. |
| CBS36 | 435 350 | 6 292 360 | 18.07.89 | 18.07.89 | 9 | 216.534 | 217.416 | 2 - 8 | 216.108 | 7 320 | 3.3 | obs. |
| CBS37 | 437 820 | 6 294 570 | 20.07.89 | 20.07.89 | 13 | 230.279 | 230.982 | 2 - 8 | 227.452 | 9 350 | 8.6 | obs. |
| CBS38 | 440 100 | 6 295 340 | 05.08.89 | 05.08.89 | 12 | 232.480 | 233.316 | 1.7 - 10.7 | 232.221 | 6 320 | 2.9 | obs. |
| CBS39 | 436 860 | 6 296 370 | 26.07.89 | 27.07.89 | 23 | 242.519 | 243.451 | 11 - 23 | 232.341 | 2 460 | 0.6 | obs. |
| | | | | Aggregate depth | 1 662 | | | | | | | |

NOTE:

(a) Surveyed co-ordinates by Griffin Coal Mining Co. Ltd

(b) Bore not constructed to design specifications

(c) December 1989

(d) Bailed sample

(e) Little or no airlift flow obtained

bns below natural surface

abd abandoned

obs observation

examinations were undertaken on 18 samples from 11 of the bores (Backhouse, 1990).

The bores were levelled to the Australian Height Datum either by the Surveys and Mapping Division of the Department of Mines, or by the Griffin Coal Mining Company. Geophysical logging of six bores, CBS4, CBS5, CBS14, CBS16, CBS21 and CBS29, was undertaken by the mining companies on whose tenements the bores are located.

The bores were developed by airlifting and water samples were submitted to the Chemistry Centre (W.A.) for chemical analysis.

Waterlevels in all bores were recorded at monthly intervals (Moncrieff, 1990) and, between December 1989 and February 1991, waterlevels in six bores (CBS14A, CBS14B, CBS17A, CBS17B, CBS21A and CBS21D) were continuously monitored. Additional watertable information from existing bores was supplied by SECWA and the mining companies.

A summary of the bore data is given in Table 1 and more detailed information is available in Moncrieff (1991a,b).

# Geology

## Setting

The Collie Basin is a small Permian sedimentary basin on the southwestern Yilgarn Craton and contains remnants of a once-extensive Permian cover over the Precambrian rocks of the region (Wilson, 1990). Two similar but smaller basins, the Wilga and the Boyup Basins, lie about 15 km and 30 km respectively south of the Collie Basin (Fig. 1). Sedimentary rocks analogous to those in the Collie Basin occur in the southern Perth Basin.

The Collie Basin is bilobate in plan and elongate parallel to the dominant northwesterly structural trend of the surrounding Yilgarn Craton (Fig. 2). The lobes are separated by a fault-controlled basement high, the Stockton Ridge and its subsurface extension, which divides the basin into the Cardiff and Premier Sub-basins (Wilson, 1990). The Premier Sub-basin includes the Muja and Shotts Sub-basins recognized by Lord (1952). There are about 1000 m of Permian sedimentary rocks in the Collie Basin (Le Blanc Smith, 1993).

The margin of the Collie Basin and the Permian strata inside the basin are concealed by a veneer of Cretaceous and Cainozoic sedimentary rocks. The basin boundary is mainly faulted; elsewhere it is an unconformity and has been inferred from geological mapping, gravity surveys and limited bore data. The drilling intersected both Permian and Cretaceous strata outside the basin margin shown by Gozzard and Jordan (1986, 1987) and Wilson (1990) but, because these strata were either thin (<20 m) or not fully penetrated, the previously accepted basin boundary is used in this report.

## Stratigraphy

The stratigraphic succession in the area is given in Table 2. The descriptions which follow of the units intersected by the drilling are intentionally brief as detailed lithological descriptions may be found in Wilson (1990). The rock units in the Collie Basin are lithologically similar and consequently boundaries in boreholes are often difficult to recognize.

### *Yilgarn Craton*

Granitic rocks of the Yilgarn Craton are exposed outside the basin, and close to the basin margin in several places (Fig. 4). The drilling outside the basin intersected granitic, gneissic, schistose, or doleritic rocks, or overlying weathered profile at 11 sites. Within the basin, only drillhole CBS11 intersected basement. Previous drilling has shown that the basement immediately underlying the sedimentary rocks in the basin is smooth and striated in places (Low, 1958), but a 0.6 m-thick weathered section was penetrated above fresh basement in CBS11 (Moncrieff, 1991a).

### *Stockton Formation*

The Stockton Formation which consists of claystone, sandstone, mudstone, and tillite was intersected at three sites (CBS11, CBS35 and CBS36), and possibly at two others (CBS7 and CBS39) where weathering has made identification difficult. Bores CBS35 and CBS36 are located south of the previously proven extent of the formation in the Cardiff Sub-basin. The formation was fully penetrated in CBS7, CBS11 and CBS39 attaining a maximum thickness of 11 m in the latter bore. Elsewhere its maximum known thickness is 330 m in the Cardiff Sub-basin and 60 m in the Premier Sub-basin (Wilson, 1990). The thickness of the formation varies greatly due to its deposition on an undulating basement. The formation unconformably overlies Precambrian crystalline rocks and is conformably overlain by the Collie Coal Measures.

An Early Permian age (Asselian to Sakmarian) is assigned to the Stockton Formation, and sedimentary structures and microflora indicate subaqueous deposition during periglacial or cold-temperate climatic conditions (Wilson, 1990). Samples from the formation from CBS11 are assigned to the *Pseudoreticulatispora confluens* Zone or Stage 2 (Backhouse, 1991).

### *Collie Coal Measures*

The Collie Coal Measures were intersected at 26 sites although the base was penetrated only at CBS11. The maximum thickness drilled is about 344 m in CBS5A: the position of the unconformity which defines the base of the overlying Nakina Formation is uncertain in this bore. A weathered section from about 30 m to 235 m (GF 3, Fig. 1) thick, depending on the depth and thickness of major coal and shale beds, occurs at the top of the formation. The Collie Coal Measures have a stratigraphic thickness of about 1050 m, of which the top 975 m is coal bearing (Le Blanc Smith, 1993); however, because of

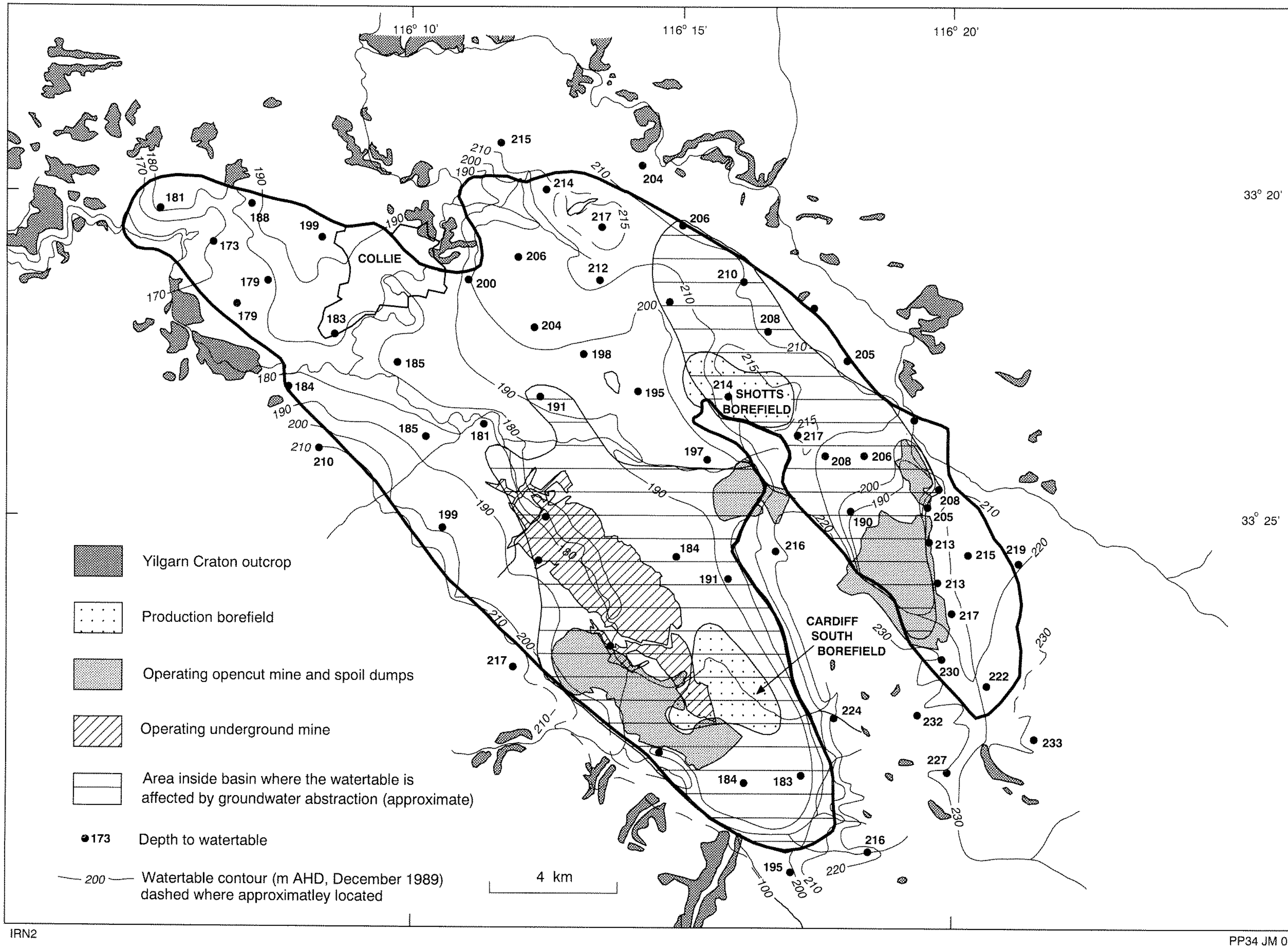


**Figure 4. Watertable, December 1989**

**Table 2. Stratigraphic units in the Collie Basin (modified after Park, 1983)**

| | | | COLLIE BASIN | |
|---|---|---|---|---|
| | | | CARDIFF SUB-BASIN | PREMIER SUB-BASIN |
| CRETACEOUS | | | Nakina Formation | |
| PERMIAN | UPPER | Collie Coal Measures | Cardiff Member | Muja Member |
| PERMIAN | UPPER | Collie Coal Measures | Collieburn Member | Premier Member |
| PERMIAN | LOWER | Collie Coal Measures | Ewington Member | |
| PERMIAN | LOWER | Stockton Formation | | |
| PRECAMBRIAN | | | Yilgarn Craton | |

faulting, the maximum drilled thickness is only about 740 m (GDD 'B', Fig. 1). The formation is unconformably overlain by the Nakina Formation.

A light-coloured, variable-grained, at times pebbly sandstone, which contains varying amounts of clay, constitutes about 60% of the Collie Coal Measures. The sandstone in the weathered section at the top of the formation is usually poorly lithified but with depth it becomes more indurated. Cavities, of uncertain origin, have been intersected by many bores. In the southern Premier Sub-basin cavities occur near coal seams and faults, and may be up to 4.5 m deep and extend for hundreds of metres (Vogwill and Brunner, 1985).

Pale siltstone and black shale were intersected in millimetre- to centimetre-scale interbedded sections up to 1.5 m thick. Core from these sections has a distinctive layered appearance. Typically the proportion of shale increases upward and the rock may grade into shale or carbonaceous shale.

The coal-bearing parts of the Collie Coal Measures consist of cyclic, upward-fining sequences of sandstone, siltstone, shale and coal, each resting on an erosional base (Wilson, 1990). Cycles are sometimes incomplete and parts of each may be repeated before the next cycle commences. In the CBS bores, cycles range from 3 m to 13 m in thickness and exhibit structures (bedding, laminations, cross-stratification, etc.) similar to those described by Wilson (1989). The major coal-bearing strata in each sub-basin are grouped into three members (Table 2) whose subcrop distribution is shown in Figure 2. Individual coal seams are generally less than 4 m thick but range from centimetre scale to 13 m. Seam washouts and seam partings occur in places. The coal seams of the lowermost Ewington Member can be broadly correlated over the entire basin whereas the overlying sequence is more variable and correlations have proved difficult (Park, 1982; Kristensen and Wilson, 1986; Davy and Wilson, 1989). Unnamed sequences up to 300 m thick separate the members. These consist mainly of silty and clayey sandstone and sandy mudstone, but include some coal seams (Backhouse, 1991).

The Collie Coal Measures were deposited during the Permian (Sakmarian, probably to Kazanian) in a fluvial (braided stream) environment (Wilson, 1990). Samples from the bores ranged from the *Pseudoreticulatispora confluens* to the *Protohaploxypinus rugatus* zones (Backhouse, 1991).

### *Nakina Formation*

The Nakina Formation was intersected in 28 bores and attains a probable maximum thickness of 23 m in CBS28. Although the maximum known thickness of the formation is about 30 m, considerable variation results from its deposition on the undulating and eroded surface of the Collie Coal Measures, and from post-depositional erosion. The contact with the Collie Coal Measures is indistinct in many of the bores. Alluvial, eolian, and swamp deposits unconformably overlie the formation and a laterite capping is present in topographically high areas. A palaeochannel infilled with sand and gravel extending from the Stockton Ridge to the Muja opencut mine area has been intersected in boreholes (Brunner, I., 1989, pers. comm.).

The formation consists of sandstone and mudstone with lesser amounts of claystone and conglomerate, all of which are usually poorly lithified. Thin bedding and cross-bedding are well developed in exposures at the Muja opencut. The sandstone which ranges from clean to clayey and silty, is predominantly light coloured, coarse grained and poorly sorted. Where the proportions of clay and silt increase it grades into mudstone. A thin basal pebble conglomerate was intersected in a few bores and a basal ferruginized section also occurs in places.

The Nakina Formation is believed to be a fluvial deposit (Wilson, 1990) and consists of detritus eroded from the Yilgarn Craton or reworked from the Collie Coal Measures. Backhouse and Wilson (1989) have assigned an Early Cretaceous age to the basal part of the formation based on its palynological similarity to the Leederville Formation of the southern Perth Basin. No suitable samples for palynological examination were obtained during the drilling program.

### *Laterite and sand*

Laterite is developed both on the sedimentary rocks of the Collie Basin and on the crystalline rocks of the Yilgarn Craton. Both massive and pisolitic laterite were intersected during the drilling. In the basin, massive laterite is restricted mainly to topographically high areas, where pisolitic laterite also occurs. Elsewhere pisolitic laterite is found associated with sand and fine gravel, and may be colluvial in origin. The laterite developed over sedimentary rocks is generally sandy and is overlain in most places by a thin cover of pale- to medium-grey, medium- to coarse-grained residual or eolian sand.

### *Alluvium, colluvium, and swamp deposits*

Broad areas of sandy alluvium and colluvium occur along most of the stream valleys inside the basin. These deposits are mainly less than 2 m thick and in this paper are collectively termed surficial sand. Alluvium conceals the Collie Coal Measures where the Collie River has incised the formation.

Swamp deposits up to about 1.5 m thick consisting of silty, clayey, slightly peaty ferruginized sandstone overlain by surficial sand, were intersected at sites CBS14 and CBS21.

## Structure

The Cardiff and the Premier Sub-basins are grabens that are deepest near their western margins. The overall structure of the Permian strata within the Cardiff Sub-basin consists of a doubly plunging, asymmetric syncline with a northwesterly axial trace along the deepest part (Wilson, 1990). This structure is overprinted with numerous faults and low-amplitude cross folds with axial traces that trend broadly northeast (Le Blanc Smith, 1989). These faults and folds complicate many of the larger structural features of the Premier Sub-basin. The Permian strata dip at low angles, but near the basin margins dips are steeper, and consequently sedimentary rocks from deeper in the succession are unconformably overlain by the flat-lying Nakina Formation.

The faults trend mainly northwest and most have normal displacements, with downthrows towards the deepest parts of the sub-basins (Fig. 2). Throws are generally less than 50 m, but range up to 200 m (Wilson, 1990); they may vary considerably along strike, or even reverse in direction (apparent scissors movement). These variations are associated with strike-slip movement along faults which penetrate the folded strata (Le Blanc Smith, 1989). Vertical displacement on the boundary faults may be as much as 1 km and may have been accompanied by considerable lateral movement.

# Hydrogeology

The main aquifers in the Collie Basin are sandstone in the Collie Coal Measures, surficial sand deposits, and sand and sandstone in the Nakina Formation. In most of the bores the watertable is in the Collie Coal Measures; generally, the shallower units are saturated only in parts of the northern and southern Premier Sub-basin, and locally near drainage lines.

The basin is surrounded by crystalline rocks with an overlying lateritic weathering profile. These rocks are of low permeability and contain mainly brackish or saline groundwater.

## Groundwater flow system

In the Collie Basin the Collie Coal Measures are in hydraulic continuity with the Nakina Formation and surficial sand and form an inhomogeneous, anisotropic, multi-layered aquifer system that has a maximum saturated thickness of about 1050 m. The thickness of permeable sandstone in the aquifer system, averaged over the basin, is estimated to be about 325 m. The basin contains a regional groundwater flow system which is unconfined near the surface and confined at depth. Individual sandstone aquifers in the Collie Coal Measures are separated by confining beds of shale and coal; however, hydraulic connection across them may occur (Hammond and Boyd, 1988). Porosity is mainly intergranular but fracture porosity also occurs at depth (Vogwill and Brunner, 1985).

The flow system is bounded at the top by the watertable and at the base by impermeable claystone of the Stockton Formation, or by basement rocks (where the Stockton Formation is absent). Laterally, there is hydraulic connection across the basin margin in both the Nakina Formation and the surficial sand; however, the saturated thickness is believed to be small and, for the purpose of this paper, the flow-system boundary is assumed to coincide with the basin margin. Superimposed on the regional flow system within the basin are inferred local groundwater flow systems near surface water features, and also structurally controlled intermediate groundwater flow systems (Fig. 5).

Groundwater flow in the basin is complex due to the vertical stacking of aquifers and lateral stratal discontinuities caused by faulting, washouts, attenuation of beds, and mine workings. Faults may be either permeable or impermeable depending on the lithologies that are in contact across them (Vogwill and Brunner, 1985). Furthermore, faults may exert some structural control on groundwater flow at depth. Uncased exploration bores, bores in which the casing has failed, and poorly constructed bores may also facilitate groundwater movement across confining beds. The interpretation of groundwater flow is further complicated by the effects of large-scale groundwater withdrawals.

Regional groundwater flow at depth is poorly understood. Most existing deep groundwater-observation bores have been constructed to monitor the effects of pumping at operating mines or to provide baseline groundwater information in areas where mines are proposed. These bores are open only at stratigraphic levels which are of interest for groundwater control at the mines, but data from them have locally provided a good understanding of the hydrogeology. The remaining deep groundwater-observation bores in the basin are open mainly over several intervals and at different stratigraphic levels, and data from them are unsuitable for determining the regional groundwater flow system.

### *Watertable configuration*

The configuration of the watertable (Fig. 4) is broadly a subdued replica of the topography. The highest groundwater levels (about 230 m AHD) coincide with the

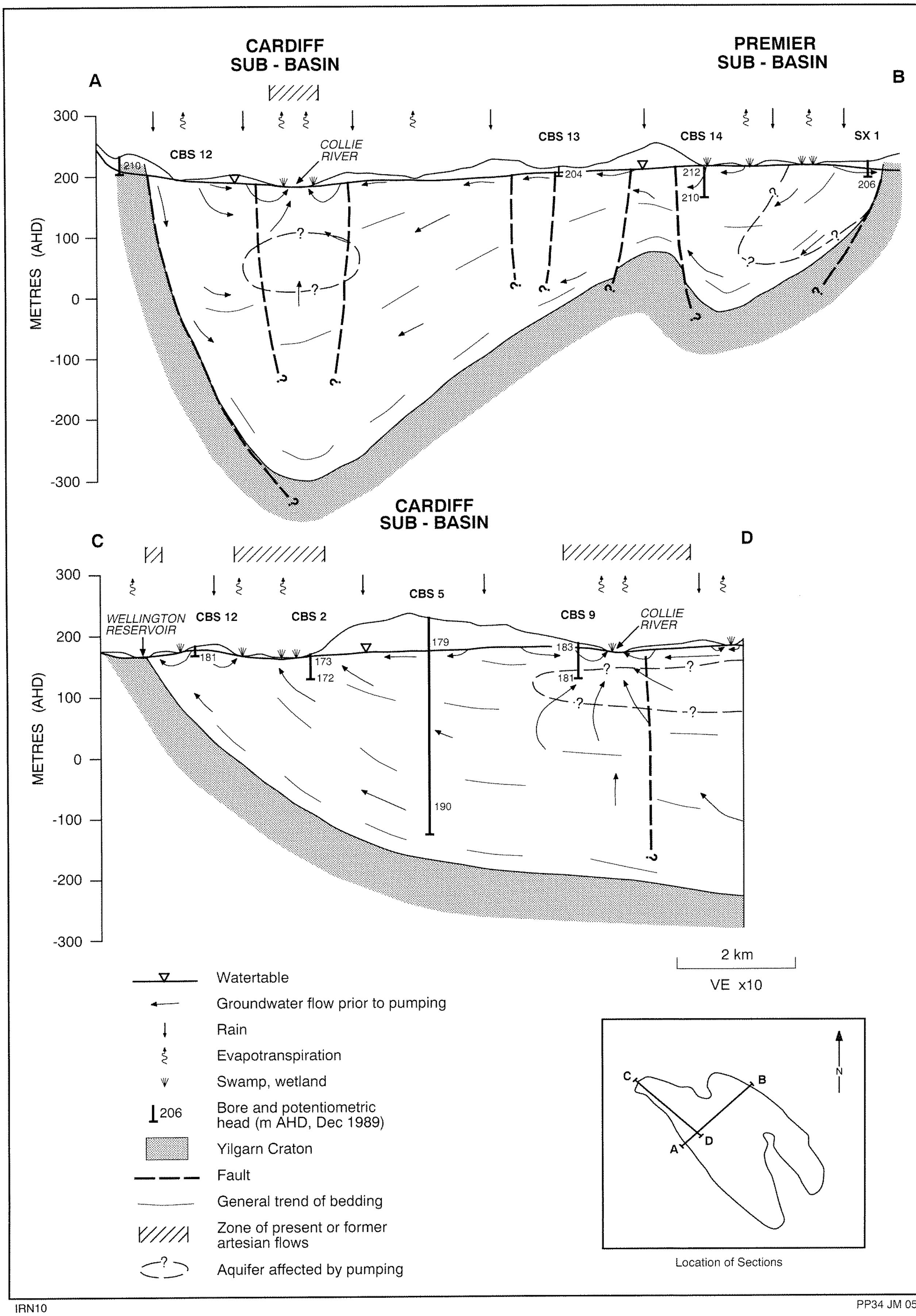


**Figure 5. Diagrammatic sections showing conceptual groundwater flow in the northern Collie Basin**

topographic divide between the South and East Branches where a groundwater mound extends along the Stockton Ridge and into the northern Premier Sub-basin. The sedimentary rocks are unsaturated in CBS22 on the eastern side of the mound near the margin of the basin where fresh basement was intersected at 10.5 m depth. The zone above fresh basement is also unsaturated on parts of the Stockton Ridge. The highest watertable elevations along the southwestern margin of the basin parallel the topographic divide between the South Branch and the Preston River to the west.

The watertable slopes down towards the South and East Branches, towards Chicken Creek, and locally towards smaller drainage lines inside the basin. The hydraulic gradient is steepest around the edges of the southern Cardiff Sub-basin, locally around some streams in the northern Cardiff and Premier Sub-basins, and adjacent to opencut mines. Permanent wetlands occur where the watertable is at the surface. Temporary perched watertables have been observed in the Nakina Formation after heavy rain (Brunner, I., 1990, pers. comm.).

### *Potentiometric-head distribution*

Potentiometric heads in the deeper CBS bores (that are open about 50 m below the watertable), in PWD5/80 which is alongside CBS18, and in selected deep SECWA bores are shown in Figure 6. The highest heads occur in the Premier Sub-basin (211 m AHD in ME1) and the lowest in the central Cardiff Sub-basin (164 m AHD in CBS17B).

Between September 1989 and February 1991, a downward head gradient was observed between the watertable and the deeper intervals in the flow system at most sites where heads from multiple-depth intervals are recorded (Fig. 6). The steepest gradient occurred at CBS17, where the maximum head difference was 16.69 m over 35 m depth (July 1990, Table 3), and is a consequence of pumping for groundwater control at the underlying WD2 mine (at a depth of about 150–200 m). A downward head potential of 8.65–9.81 m over 43 m depth occurred at CBS21 on the northeastern margin of the Premier Sub-basin. The hydraulic head at depth here may be depressed due to abstraction of groundwater from the Shotts Borefield for water supply to the Muja Power Station (Fig. 6).

The largest upward head gradient, of 10.80–11.84 m over 245 m depth, was observed at CBS5 in the northern Cardiff Sub-basin (Table 3). The deep observation interval at this site (CBS5A) is 257 m below the watertable. Upward head gradients were also observed during December 1989 at CE1 and CE2 in the southern Cardiff Sub-basin, where groundwater heads are affected by pumping. At 3 sites (CBS18, SE1 and MX6) there was no difference between the heads recorded from the shallow and the deep intervals.

### *Recharge*

Recharge to the watertable is mainly by direct infiltration of rainfall. Groundwater recharge also occurs from the South Branch in the southern Cardiff Sub-basin, where the river stage is higher than the watertable during most of the year and, seasonally, by seepage from streams which rise outside the basin and flow onto permeable Collie Basin sediments. Discharge from mine dewatering also provides groundwater recharge.

Rainfall recharge is concentrated during the period of highest rainfall, between May and September. The amount of recharge varies annually and spatially as indicated by different hydrograph responses (Moncrieff, 1991b). Annual variations are caused mainly by differences in the amount and intensity of rainfall. Areal variations result primarily from differences in permeability at the surface. Surficial sand, which occurs over large areas of the basin, favours infiltration of rainfall and groundwater recharge, particularly where the watertable is in the sand or where the sand is underlain by permeable sandstone. Groundwater recharge is enhanced by a decrease in evapotranspiration from areas where the watertable has been lowered by groundwater abstraction.

Total groundwater recharge to the basin is estimated to be 31 x $10^6$ m$^3$/year and the net average rainfall recharge about 26 x $10^6$ m$^3$/year (13% of average rainfall) based on the following water balance for the basin.

Surface water: **If** + **GD** + **RO** + **Re** = **Of**
($10^6$ m$^3$/year) 122 + 4 + 15 + 14 = 155

Groundwater: **RR** (= **GR** + **IR**) + **XR** = **GD** + **Ab** + **s**
($10^6$ m$^3$/year) 26 (= 25 + 1) + 5 = 4 + 39 + (-12)

where:
- **If** = surface water inflow,
- **GD** = groundwater discharge to streams (baseflow),
- **RO** = rainfall runoff (from inside the basin),
- **Re** = the amount of water that is discharged to streams after abstraction at borefields or mines,
- **Of** = surface water outflow,
- **RR** = rainfall recharge,
- **GR** = groundwater recharge from rainfall,
- **IR** = induced recharge due to decreased evapotranspiration from about 100 km$^2$ of the basin where the watertable is depressed due to groundwater abstraction (Fig. 4),
- **XR** = extra-basin recharge from streams which flow into the basin,
- **Ab** = the volume of groundwater being pumped from borefields and mine groundwater-control operations,
- **s** = change in groundwater storage.

Surface water flow and runoff have been calculated from data in Loh and Stokes (1981).

Recharge can also be estimated from chlorinity data. The average chlorinity of rainfall in the Collie area estimated from data collected at other rainfall stations in the region (Hingston, F., 1990, pers. comm.) is about 7 mg/L. The chlorinity of water samples collected from



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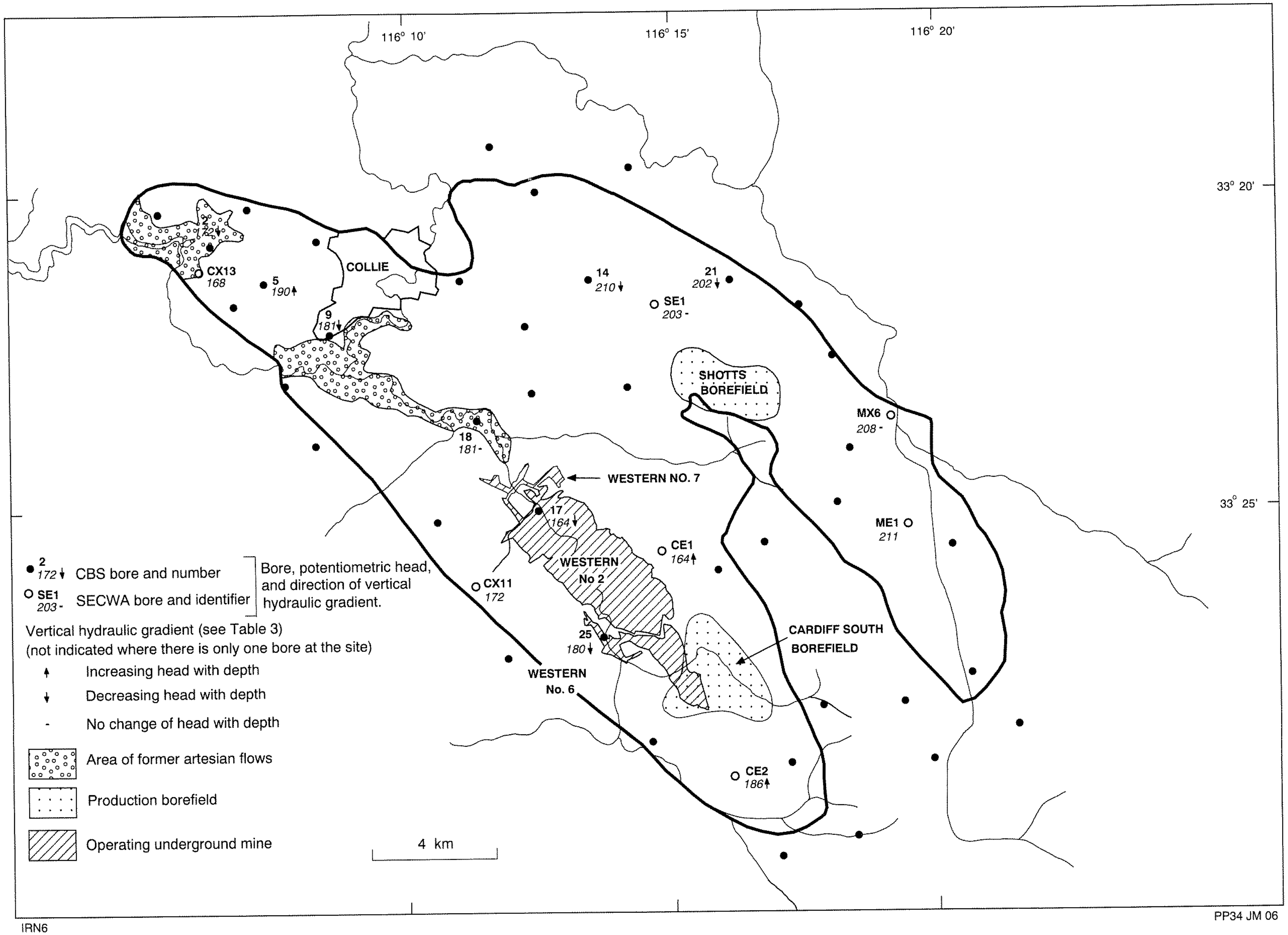


**Figure 6. Potentiometric-head distribution, December 1989**

bores in sandy areas of the basin, where the watertable is shallow, ranged from 13 mg/L in CBS2A to 35 mg/L in CBS14A. These values indicate local recharge rates of 20–50% of rainfall but, because of variations in the depth to the watertable, and the variable nature of the sediments above and below the watertable, the average recharge over the basin is likely to be less than this.

The watertable in the bores in both 1989 and 1990 was usually highest during September–October, after the period of most rainfall, and lowest during April–May, at the end of summer. However, there was considerable variation, particularly of the lowest waterlevels, around these times. Also, in many bores, the timing and magnitude of waterlevel changes have been modified due to drawdowns caused by groundwater abstraction from the basin (Fig. 4).

A comparison of waterlevels recorded in May and October 1990 shows a rise of the watertable at most sites (Fig. 7). Inside the basin, in the areas largely unaffected by pumping, the patterns of watertable rise varied. In the northern Premier Sub-basin rises were uniformly 0.5–1.0 m whereas they were more inconsistent in the northern Cardiff Sub-basin (0.1–2.3 m). Part of this inconsistency is due to the large variations in the depth to the watertable in the northern Cardiff Sub-basin compared with those in the northern Premier Sub-basin. The level of the watertable in bores on the eastern side of the Cardiff Sub-basin (CBS19, CBS26 and CBS33) and in the central Premier Sub-basin (CBS24 and CBS29) decreased due to drawdowns caused by pumping from the basin.

The largest watertable rises between May and October 1990 occurred outside the basin on the Stockton Ridge in CBS27 (3.2 m) and CBS39 (8.3 m). CBS27 is sited alongside a wetland where groundwater recharge is concentrated by seasonal flow in an adjacent stream. The watertable in the bore rises sharply with the onset of streamflow, usually in April–May, and falls gradually after streamflow ceases around September. In CBS39, about 7 m of the watertable rise occurred during July 1990 and a watertable fall of similar magnitude occurred during January 1991. The reasons for these sudden watertable changes, which are followed by periods of comparatively small fluctuations, are uncertain.

### *Groundwater flow*

Regional groundwater flow is strata controlled in the Collie Coal Measures. Shale or coal units retard both vertical groundwater movement and, where they intersect the watertable, lateral groundwater movement. Unconfined groundwater flow occurs in the surficial sand or in the Nakina Formation where the watertable is above the Collie Coal Measures. Flow in the Nakina Formation may be locally concentrated in palaeochannels.

Regional groundwater flow, based on the apparent hydraulic gradient of the watertable, is mainly northeast and southwest towards the South and East Branches, Chicken Creek and, particularly in the northern Premier Sub-basin, to tributaries of the East Branch which flow from the basin (Fig. 4). Groundwater flow is diverted towards the Muja and WO5 opencut mines in the southern parts of the sub-basins.

There is potential for vertical movement of groundwater under the prevailing vertical hydraulic gradients in the basin (Table 3). Downward flow from the watertable to deeper parts of the flow system occurs where there is a downward head potential but the amount is uneven areally and depends on the nature of the rock units in the Collie Coal Measures. Increased vertical hydraulic gradients established as a result of groundwater abstraction at depth also promote downward groundwater flow from the watertable. Downward flow is probably concentrated in the northern Premier Sub-basin and along the basin margin where the elevation of the watertable is sufficient to initiate downward flow (Fig. 5). Steeper dipping strata near the margin enables flow to move deeper into the basin.

The areas where there is upward groundwater flow are indeterminate. There is potential for groundwater movement from the base of the flow system under the upward hydraulic gradient that exists in the northern Cardiff Sub-basin (CBS5). There may also be upward flow along the eastern side of the sub-surface extension of the Stockton Ridge in the northern Premier Sub-basin (Fig. 5).

The direction of regional groundwater flow in the deeper parts of the flow system is uncertain but is thought to be towards the South Branch. Flow is also diverted towards areas of groundwater abstraction but the areal extent of diverted flow is not known. There is probably groundwater flow across the sub-surface extension of the Stockton Ridge from the Premier to the Cardiff Sub-basin (Fig. 5).

### *Discharge*

Groundwater discharge occurs by evapotranspiration, baseflow to the Collie River and its tributaries, and pumping (see *Abstraction*).

Evapotranspiration has been estimated to account for about 90% of the rain (90% of 171 x $10^6$ $m^3$) that falls onto the Collie Basin (Collie Land Use Working Group, 1987). Part of this is evaporated from wetlands or transpired by vegetation which draws water directly from the watertable. The effects of evapotranspiration have been observed in both CBS14A and CBS21A, which are alongside wetlands, and where the watertable appears to fluctuate diurnally. The hydrograph of CBS14A for February 1990 (Fig. 8) shows that the watertable is usually lowest in the late afternoon, after the hottest part of the day, and highest soon after dawn. The average waterlevel change within this period (0.026 m) is at the limit of the accuracy of the recording instrument. Nevertheless, the fluctuations are believed to be real because the waterlevel in the deeper bore at the site does not exhibit similar fluctuations.

Baseflow occurs in the northern Cardiff Sub-basin where the watertable is not affected by pumping and the Collie River is a gaining stream (Fig. 5). Groundwater discharge to tributaries of the Collie River is shown by re-entrants in the watertable contours on Figure 4. The tributaries which rise in the northern Premier Sub-basin

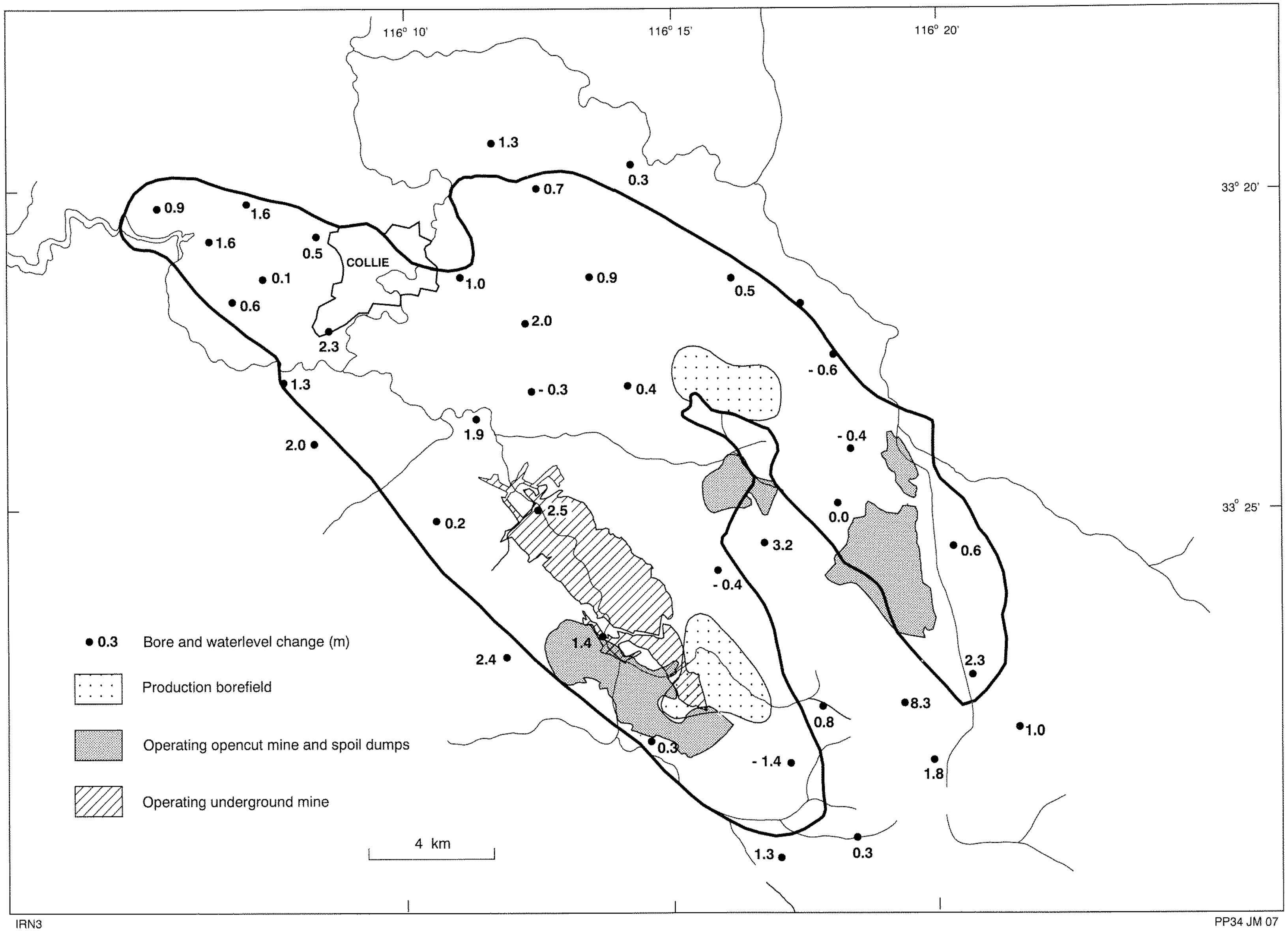


**Figure 7. Waterlevel change, May to October 1990**

Table 3. Groundwater head difference with depth

| *Bores CBS* | *Vertical separation of intervals (m)* | *Head difference (m)* | | | | *Direction (a)* |
|---|---|---|---|---|---|---|
| | | *Max.* | *Date* | *Min.* | *Date* | |
| 2A<br>2B | 34 | 1.83 | 14.08.90 | 1.40 | 04.09.89 | down |
| 5B<br>5A | 245 | 11.84 | 20.11.90 | 10.80 | 11.09.90 | up |
| 9A<br>9B | 41 | 2.48 | 11.09.90 | 1.16 | 13.06.90 | down |
| 14A<br>14B | 13 | 1.78 | 19.06.90 | 0.57 | 12.12.89 | down |
| 14B<br>14C | 17 | 1.68 | 22.11.90 | 1.28 | 19.06.90 | down |
| 14A<br>14C | 30 | 3.06 | 19.07.90 | 1.90 | 07.02.91 | down |
| 17A<br>17B | 35 | 16.69 | 19.07.90 | 4.64 | 05.09.89 | down |
| 18<br>PWD5/80 | 23 | 1.08 | 17.07.90 | 0.05 | 05.02.91 | down |
| 21A<br>21D | 43 | 9.81 | 15.06.90 | 8.65 | 11.10.90 | down |
| 25A<br>25B | 36 | 4.34 | 17.07.90 | 2.12 | 07.03.90 | down |

(a) up—increasing head with depth; down—decreasing head with depth

near CBS11, CBS14 and CBS21 flow into the East Branch outside the basin.

Artesian flows, implying upward groundwater head gradients and the potential for upward groundwater movement, were once common from bores drilled in topographically low areas in the northern Cardiff Sub-basin near the Collie River (Fig. 7). Flows were recorded from as shallow as 21 m below the surface (Lord, 1952). Groundwater abstraction has lowered potentiometric heads in some stratigraphic intervals in the flow system. There is now a downward hydraulic gradient between the watertable and 50 m depth in the Collie Coal Measures in this area (CBS9 Table 3) although, to the northwest, there is an upward hydraulic gradient between the base of the Collie Coal Measures and the watertable (CBS5 Table 3).

### *Abstraction*

According to SECWA and Water Authority of Western Australia data, about 39 x $10^6$ $m^3$/year of groundwater is withdrawn from production borefields and operating mines in the Collie Basin. The greater part of this is abstracted from the Collie Coal Measures, although dewatering of the Nakina Formation is also undertaken for opencut mining. The water-balance calculations indicate that some of the groundwater comes from storage. After treatment to raise the pH and remove dissolved gases and iron, most of the water is used for cooling at the Muja Power Station. The remainder is discharged either to the South Branch, from where it may be returned to the groundwater flow system by leakage from the river bed, or to Chicken Creek, which flows out of the basin. The groundwater that is discharged directly to Chicken Creek is also first treated to raise the pH and remove iron. Some groundwater is pumped from the basin for use in sawmilling and there is minor groundwater abstraction by private users for domestic purposes and stock watering.

Groundwater withdrawals have affected the watertable over an estimated 100 $km^2$ of the basin (Fig. 4). The areas influenced are difficult to define accurately because the effects are generally small and are often difficult to distinguish from seasonal watertable fluctuations. The effect on the watertable is also influenced by the location of the abstraction and geological structure.

Depressions in the watertable are centred mainly around groundwater abstraction areas and result either from pumping in the upper part of the flow system or from downward leakage through confining beds to deeper parts of the flow system where groundwater heads are affected by abstraction. Hydrographs from site CBS17 (Fig. 9), above the WD2 underground mine, show there was a drawdown of 11.8 m in CBS17B (slotted interval about 33 m below the watertable) and 2.8 m in CBS17A (open interval at the watertable) between November 1989 and May 1990. Much of the drawdown of the watertable is probably due to vertical leakage of groundwater to deeper intervals in the Collie Coal Measures, although some results from seasonal fluctuation. The watertable recovers when flow recommences in the adjacent South Branch. This usually occurs in autumn and is due to groundwater recharge by leakage from the river. The watertable variation in CBS17A reflects the change of about 3 m in river level during 1990.

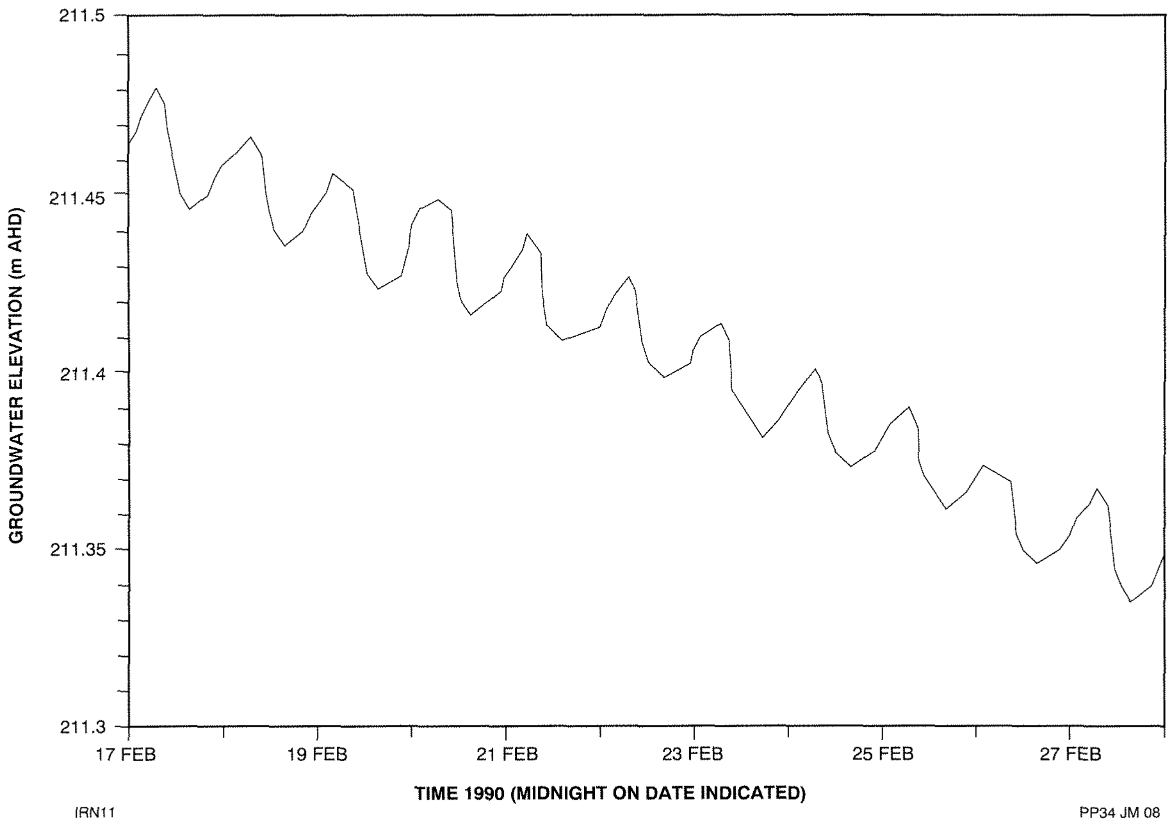


**Figure 8. Hydrograph CBS14A**

The watertable may also be depressed in more distant areas where sandstone aquifers which are being depressurized at depth are either present at the watertable, or in direct contact with the overlying Nakina Formation below the watertable. In the southern Cardiff Sub-basin the effects of pumping at the Cardiff South Borefield and the WO5 opencut mine extend to near the southern margin of the basin (CBS33) and, in the Premier Sub-basin, the effects of pumping at Shotts Borefield extend well north of the borefield itself (Fig. 4). The elevation of the watertable in CBS33 has declined steadily since recordings began in September 1989 and, by the beginning of May 1991, it had fallen by 6.4 m to 58.8 m below the natural surface (Moncrieff, 1991b).

Depressions in the watertable surround the WO5, Muja/Chicken Creek and, to a lesser extent, the WO3 opencut mines. In these areas groundwater is drawn directly from the upper part of the flow system as well as from deeper intervals. The Nakina Formation is completely dewatered in the mine areas and the pumping has caused partial dewatering and the formation of perched watertables in some aquifers in the Collie Coal Measures (Vogwill and Brunner, 1985). Dewatering at the Muja opencut has allowed mining to progress to a depth of about 200 m below the original watertable.

Groundwater abstraction has greatly altered the hydraulic-head distribution at depth in the basin. The areal extent of drawdowns associated with the pumping is not known; however, it probably extends to the basin boundaries. Waterlevels have been lowered substantially around the mines and borefields. Drawdowns of as much as 110 m from pre-mining levels at the Muja opencut (Vogwill and Brunner, 1985) and 77 m at the WD7 underground mine (Hammond and Boyd, 1988) have been reported. There is limited monitoring of groundwater levels from producing intervals around the Cardiff South and Shotts borefields (Fig. 7) but drawdowns of 50–60 m occur in the production bores themselves.

Flow of the South Branch in the southern Cardiff Sub-basin is probably indirectly affected by the groundwater abstraction. Increased leakage of river water to the groundwater is likely to be occurring in response to the depressed groundwater levels. The duration of river flow after winter rainfall has almost certainly decreased and some of the pools that remain, which according to local residents were once permanent, are now dry for long periods.

### *Storage*

If the average thickness of sandstone above the Stockton Formation is taken to be 325 m and a specific yield of 0.1 is applied, then about 7300 x $10^6$ $m^3$ of commandable groundwater is stored in the Collie Basin. This is comparable with storage estimates of 6750 x $10^6$ $m^3$3 by the Collie Land Use Working Group (1987) and 7000 x $10^6$ $m^3$ by Allen (1991).

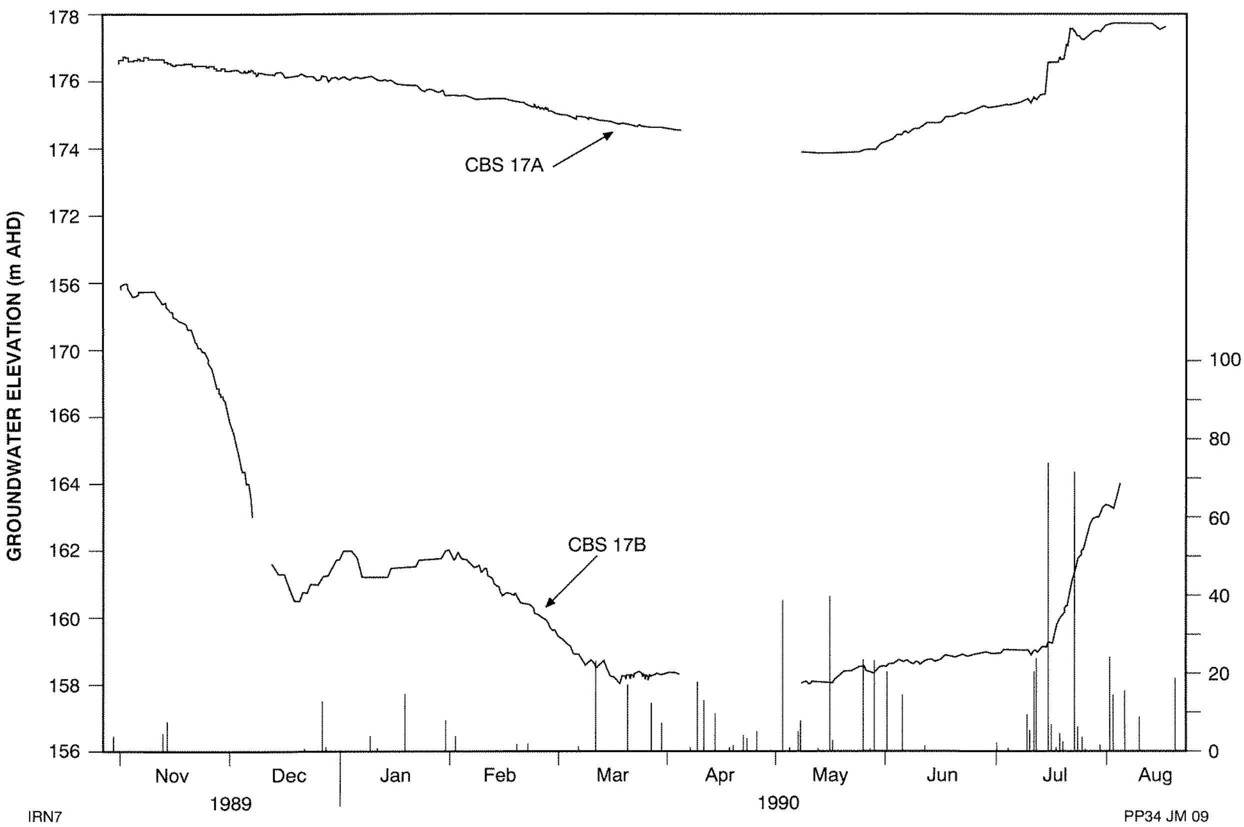


**Figure 9. Hydrographs CBS17A and CBS17B**

## Groundwater quality

### *Salinity*

The salinity of the groundwater at the watertable is highly variable (Fig. 10) and reflects local variations in lithology, topography, landuse and depth to the watertable. Consequently it is not possible to contour the data reliably. The salinity at the watertable in sandstones of the Collie Coal Measures and Nakina Formation is typically less than 750 mg/L TDS (Fig. 10). Very low-salinity groundwater (<100 mg/L) occurs where the watertable is in the upper few metres of the surficial sands (CBS2A, CBS14A, CBS18, CBS21A, and CBS34). High TDS concentrations (>1000 mg/L) occur where the watertable is in clayey sedimentary rocks. In CBS10, which is open against claystone, the salinity was 7150 mg/L.

The salinity of groundwater from the deeper intervals at seven sites where more than one bore was constructed is generally less than 500 mg/L (Fig. 10). With two exceptions the salinity at these sites increases with depth. Groundwater of comparable salinity is obtained from the Shotts and Cardiff South Borefields; elsewhere in the basin the salinity is generally less than 750 mg/L. Water discharged from the Chicken Creek mine is about 1000 mg/L.

Groundwater salinity outside the basin is highly variable. The lowest salinity groundwater occurs where the watertable is shallow and in surficial sand (70 mg/L in CBS35). Higher salinity groundwater (2000–10 000 mg/L) occurs in the weathered basement rocks on the southern part of the Stockton Ridge, and south of the Premier Sub-basin.

### *Hydrochemistry*

Chemical analyses of groundwater samples from the bores are given in Table 4. The groundwater is mainly sodium–chloride type (Fig. 11). The deeper groundwater from CBS5A is markedly different from the shallow groundwater in having a higher proportion of bicarbonate ion. The proportions of chloride and of sodium generally increase with salinity.

The sample from CBS12, which is in weathered granitic rock outside the basin, contained comparatively high proportions of both sulfate and bicarbonate ion, and a high ratio of $Na^{+}/(Ca^{++}+Mg^{++})$; however, samples from other bores in the weathered granitic rock are similar in composition to groundwater within the basin.

Groundwater inside the basin is mainly acidic; pH values from 2.6 (CBS17B) to 7.6 (CBS5A) were recorded (Table 4). The lowest pH values generally occur in bores near existing or abandoned mines (CBS11, CBS17, CBS20, CBS25 and CBS30), in bores with open intervals near shale or coal strata (CBS1, CBS8 and CBS24), and in bores in the northern Cardiff Sub-basin where the

## Table 4. Chemical analyses

| Bore Interval | Sample Number (a) | pH | Colour (TCU) | EC (mS/m @ 25°C) | TDS | T. Hard. | T. Alk. | Ca | Mg | Na | K | $HCO_3$ | Cl | $SO_4$ | $NO_3$ | $SiO_2$ | B | F | H+ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | (mg/L) | | | | | | | | | | | | | | |
| CBS1 | 93401 | 3.8 | <5 | 277 | 1 350 | 161 | <2 | 2 | 38 | 418 | 8 | <2 | 815 | 50 | 1 | 20 | 0.05 | <0.1 | 0.5 |
| CBS2A | 93402 | 5.7 | 30 | 7.6 | 40 | 16 | 3 | 3 | 2 | 9 | <1 | 4 | 13 | 12 | <1 | 2 | 0.02 | 0.1 | - |
| CBS2B | 93403 (c) | 6.0 | 5 | 18.5 | 110 | 15 | 7 | 1 | 3 | 25 | 3 | 8 | 45 | 7 | <1 | 18 | 0.02 | <0.1 | - |
| CBS3 | 93404 (b) | 6.1 | <5 | 105 | 500 | 125 | 7 | 4 | 28 | 143 | 4 | 9 | 290 | 16 | <1 | 14 | 0.03 | <0.1 | - |
| CBS4 | 93405 (b) | 5.6 | <5 | 48.6 | 240 | 31 | 4 | 1 | 7 | 75 | 1 | 5 | 137 | 7 | <1 | 7 | 0.03 | <0.1 | - |
| CBS5A | 93406 (c) | 7.6 | 35 | 36.6 | 220 | 80 | 120 | 27 | 3 | 35 | 16 | 146 | 34 | 15 | <1 | 19 | 0.03 | 0.2 | - |
| CBS6 | 93407 | 4.5 | <5 | 152 | 740 | 98 | 2 | 3 | 22 | 240 | 1 | 2 | 422 | 32 | <1 | 21 | 0.04 | <0.1 | - |
| CBS7 | 93408 | 7.7 | <5 | 217 | 1 160 | 231 | 121 | 20 | 44 | 342 | 1 | 148 | 563 | 49 | <1 | 65 | 0.04 | 0.4 | - |
| CBS8 | 93409 | 4.0 | <5 | 58.5 | 300 | 27 | <2 | 1 | 6 | 93 | 1 | <2 | 147 | 30 | <1 | 24 | 0.02 | <0.1 | - |
| CBS9A | 93410 | 5.8 | <5 | 25.7 | 130 | 25 | 3 | <1 | 6 | 37 | <1 | 4 | 70 | 6 | 3 | 8 | 0.02 | <0.1 | - |
| CBS9B | 93411 (c) | 6.0 | 5 | 109 | 560 | 129 | 11 | 9 | 26 | 150 | 10 | 14 | 310 | 17 | <1 | 27 | 0.02 | <0.1 | - |
| CBS10 | 93412 (b) | 3.0 | <5 | 1 330 | 7 150 | 1 500 | <2 | 96 | 307 | 2 170 | 27 | <2 | 4 230 | 249 | <1 | 68 | 0.04 | 0.5 | 1.7 |
| CBS11 | 93413 (b) | 2.9 | <5 | 409 | 1 990 | 385 | <2 | 21 | 81 | 591 | 17 | <2 | 1 170 | 76 | <1 | 33 | 0.06 | 0.8 | 0.9 |
| CBS12 | 93414 (c) | 6.9 | 160 | 137 | 690 | 36 | 112 | 3 | 7 | 317 | 2 | 137 | 104 | 161 | <1 | 30 | 0.05 | 0.4 | - |
| CBS13 | 93415 (b) | 3.3 | 5 | 387 | 1 950 | 542 | <2 | 26 | 116 | 533 | 9 | <2 | 1 170 | 77 | <1 | 21 | 0.12 | 0.2 | 0.4 |
| CBS14A | 93416 | 5.7 | 65 | 14.7 | 80 | 16 | 3 | <1 | 4 | 21 | 1 | 4 | 35 | 8 | <1 | 4 | <0.01 | 0.1 | - |
| CBS14B | 93417 | 5.7 | 5 | 13 | 70 | 8 | 2 | <1 | 2 | 19 | <1 | 3 | 34 | 3 | <1 | 9 | <0.01 | 0.1 | - |
| CBS14C | 93418 (c) | 5.8 | 10 | 35.5 | 170 | 30 | 4 | 2 | 6 | 49 | 1 | 5 | 93 | 10 | <1 | 10 | 0.01 | 0.1 | - |
| CBS15 | 93419 | 7.0 | <5 | 113 | 580 | 178 | 34 | 22 | 30 | 143 | 4 | 41 | 301 | 19 | 11 | 25 | 0.05 | 0.1 | - |
| CBS16 | 93420 | 5.8 | 5 | 55 | 280 | 54 | 4 | 2 | 12 | 77 | 3 | 5 | 155 | 7 | <1 | 16 | 0.01 | <0.1 | - |
| CBS17A | 93421 | 3.6 | <5 | 116 | 600 | 185 | <2 | 10 | 39 | 129 | 11 | <2 | 253 | 112 | 9 | 32 | 0.02 | 0.1 | 0.1 |
| CBS17B | 93422 (c) | 2.6 | <5 | 261 | 1 100 | 290 | <2 | 19 | 59 | 278 | 10 | <2 | 587 | 121 | <1 | 23 | 0.02 | 0.1 | 1.4 |
| CBS18 | 93423 | 5.4 | 15 | 10.9 | 70 | 8 | 2 | <1 | 2 | 15 | 2 | 2 | 26 | 13 | <1 | 10 | 0.02 | 0.1 | - |
| CBS19 | 93424 | 6.3 | 35 | 58.3 | 290 | 50 | 16 | 2 | 11 | 88 | 1 | 20 | 151 | 19 | <1 | 9 | 0.03 | 0.1 | - |
| CBS20 | 93425 | 3.7 | <5 | 141 | 680 | 100 | <2 | 2 | 23 | 214 | 3 | <2 | 380 | 37 | <1 | 17 | 0.03 | <0.1 | 0.1 |
| CBS21A | 93426 | 5.7 | 120 | 12.7 | 70 | 21 | 5 | <1 | 5 | 13 | 5 | 6 | 20 | 18 | 3 | 5 | 0.03 | <0.1 | - |
| CBS21D | 93427 (c) | 5.8 | 40 | 40.4 | 210 | 23 | 12 | 1 | 5 | 71 | 2 | 15 | 105 | 11 | <1 | 10 | 0.02 | <0.1 | - |
| CBS23 | 93428 (b) | 7.1 | 15 | 70.5 | 390 | 43 | 36 | 4 | 8 | 117 | 2 | 44 | 178 | 19 | <1 | 35 | 0.03 | 0.4 | - |
| CBS24 | 93429 | 4.5 | <5 | 90.5 | 450 | 72 | <2 | 4 | 15 | 140 | 1 | <2 | 253 | 28 | <1 | 11 | 0.04 | 0.1 | - |
| CBS25A | 93430 | 4.0 | <5 | 223 | 1 110 | 296 | <2 | 15 | 63 | 300 | 4 | <2 | 635 | 56 | <1 | 34 | 0.02 | 0.1 | 0.1 |
| CBS25B | 93431 (c) | 6.4 | 10 | 38.8 | 210 | 27 | 16 | 1 | 6 | 55 | 8 | 19 | 100 | 10 | <1 | 24 | 0.02 | <0.1 | - |
| CBS26 | 93432 | 6.0 | 5 | 76.9 | 390 | 63 | 7 | 4 | 13 | 119 | 3 | 9 | 210 | 24 | <1 | 11 | 0.04 | <0.1 | - |
| CBS27 | 93433 | 5.0 | 140 | 92.6 | 490 | 96 | 4 | 4 | 21 | 136 | 2 | 5 | 248 | 42 | 7 | 30 | 0.03 | 0.1 | - |
| CBS28 | 93434 (b) | 6.5 | 1 300 | 248 | 1 310 | 331 | 234 | 27 | 64 | 466 | 8 | 286 | 578 | 13 | 1 | 13 | 1.10 | 0.1 | - |
| CBS29 | 93435 | 5.1 | <5 | 73.7 | 370 | 68 | 2 | 4 | 14 | 108 | 8 | 2 | 209 | 10 | <1 | 19 | 0.02 | <0.1 | - |
| CBS30 | 93436 | 4.5 | 15 | 202 | 1 000 | 145 | <2 | 2 | 34 | 332 | 1 | <2 | 571 | 47 | <1 | 14 | 0.03 | 0.1 | - |
| CBS31 | 93437 | 7.3 | 10 | 418 | 2 280 | 462 | 57 | 35 | 91 | 677 | 5 | 70 | 1 290 | 99 | <1 | 43 | 0.03 | 0.1 | - |
| CBS32 | 93438 | 6.1 | 25 | 21.7 | 110 | 16 | 5 | <1 | 4 | 31 | 1 | 6 | 57 | 7 | <1 | 5 | 0.01 | <0.1 | - |
| CBS33 | 93439 (c) | 6.4 | 60 | 136 | 730 | 179 | 58 | 24 | 29 | 215 | 12 | 71 | 323 | 80 | <1 | 13 | 0.04 | 0.1 | - |
| CBS34 | 93440 | 6.3 | 30 | 13.4 | 70 | 21 | 14 | 2 | 4 | 15 | 2 | 17 | 24 | 9 | 1 | 7 | 0.03 | <0.1 | - |
| CBS35 | 93441 | 6.1 | 5 | 13.2 | 70 | 16 | 9 | <1 | 4 | 15 | 2 | 11 | 29 | 7 | 2 | 6 | 0.01 | <0.1 | - |
| CBS36 | 93442 | 6.4 | 5 | 1 300 | 7 320 | 1 690 | 20 | 48 | 383 | 2 170 | 8 | 24 | 4 390 | 225 | <1 | 83 | 0.02 | 0.4 | - |

**Table 4. (continued)**

| *Bore Interval* | *Sample Number (a)* | *pH* | *Colour (TCU)* | *EC (mS/m @ 25°C)* | *TDS* | *T. Hard.* | *T. Alk.* | *Ca* | *Mg* | *Na* | *K* | *$HCO_3$* | *Cl* | *$SO_4$* | *$NO_3$* | *$SiO_2$* | *B* | *F* | *H+* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | *(mg/L)* | | | | | | | | | | | | | | |
| CBS37 | 93443 | 6.8 | 5 | 1 640 | 9 350 | 2 640 | 32 | 156 | 548 | 2 670 | 11 | 39 | 5 540 | 364 | <1 | 37 | 0.02 | 0.1 | - |
| CBS38 | 93444 | 4.5 | <5 | 1 130 | 6 320 | 1 530 | <2 | 68 | 330 | 1 920 | 5 | <2 | 3 830 | 121 | <1 | 48 | 0.01 | 0.3 | - |
| CBS39 | 93445 | 6.7 | 5 | 458 | 2 460 | 544 | 23 | 35 | 111 | 729 | 6 | 28 | 1 440 | 77 | <1 | 48 | 0.02 | 0.6 | - |

NOTE:

(a) Airlift samples taken about 1 month after completion of bore following further development

(b) Airlift samples taken at completion of bore only

(c) Airlift samples taken at completion of development

TCU True colour units

EC Electrical conductivity

TDS Total dissolved solids (by calculation)

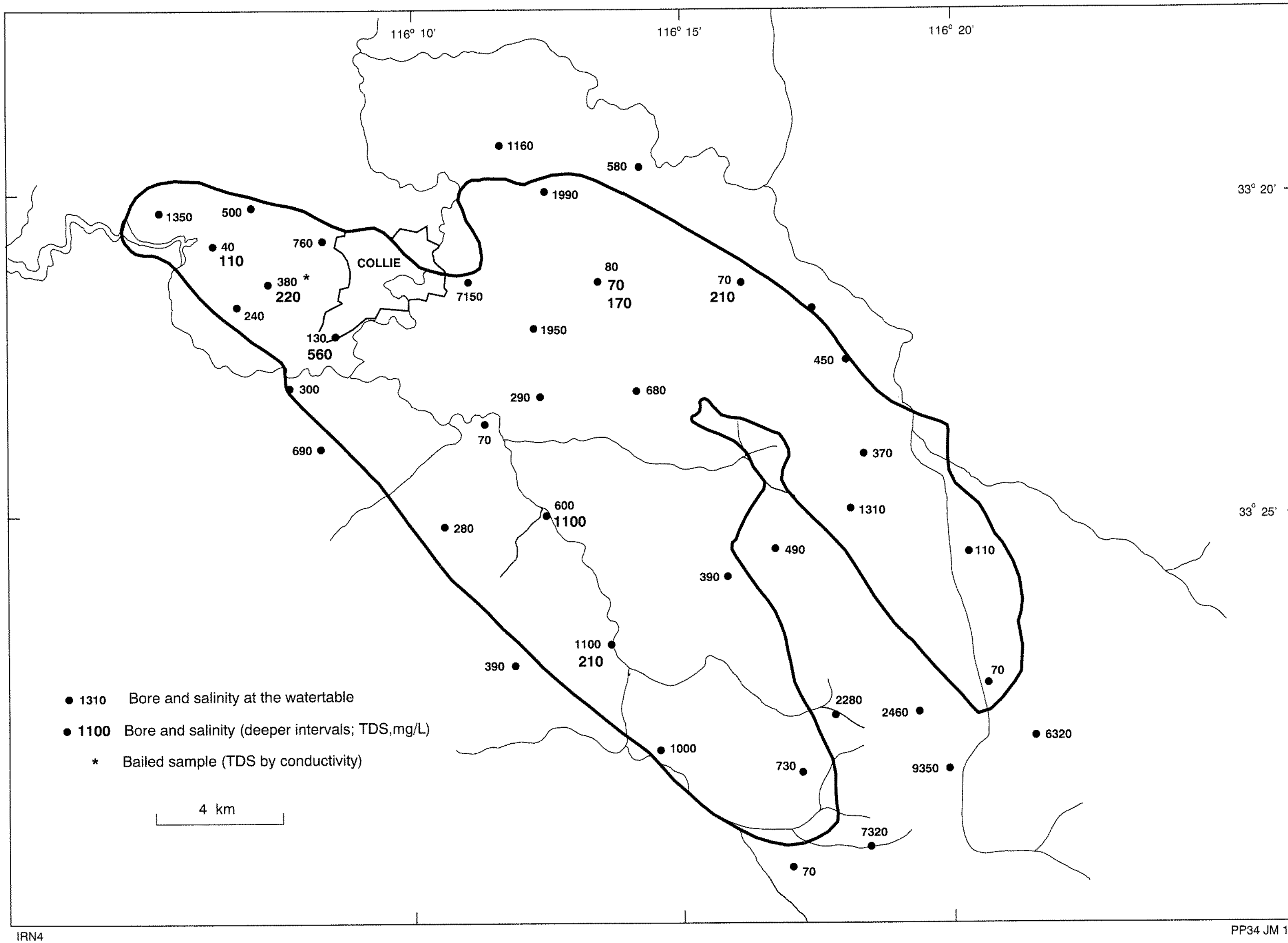


**Figure 10. Groundwater salinity**

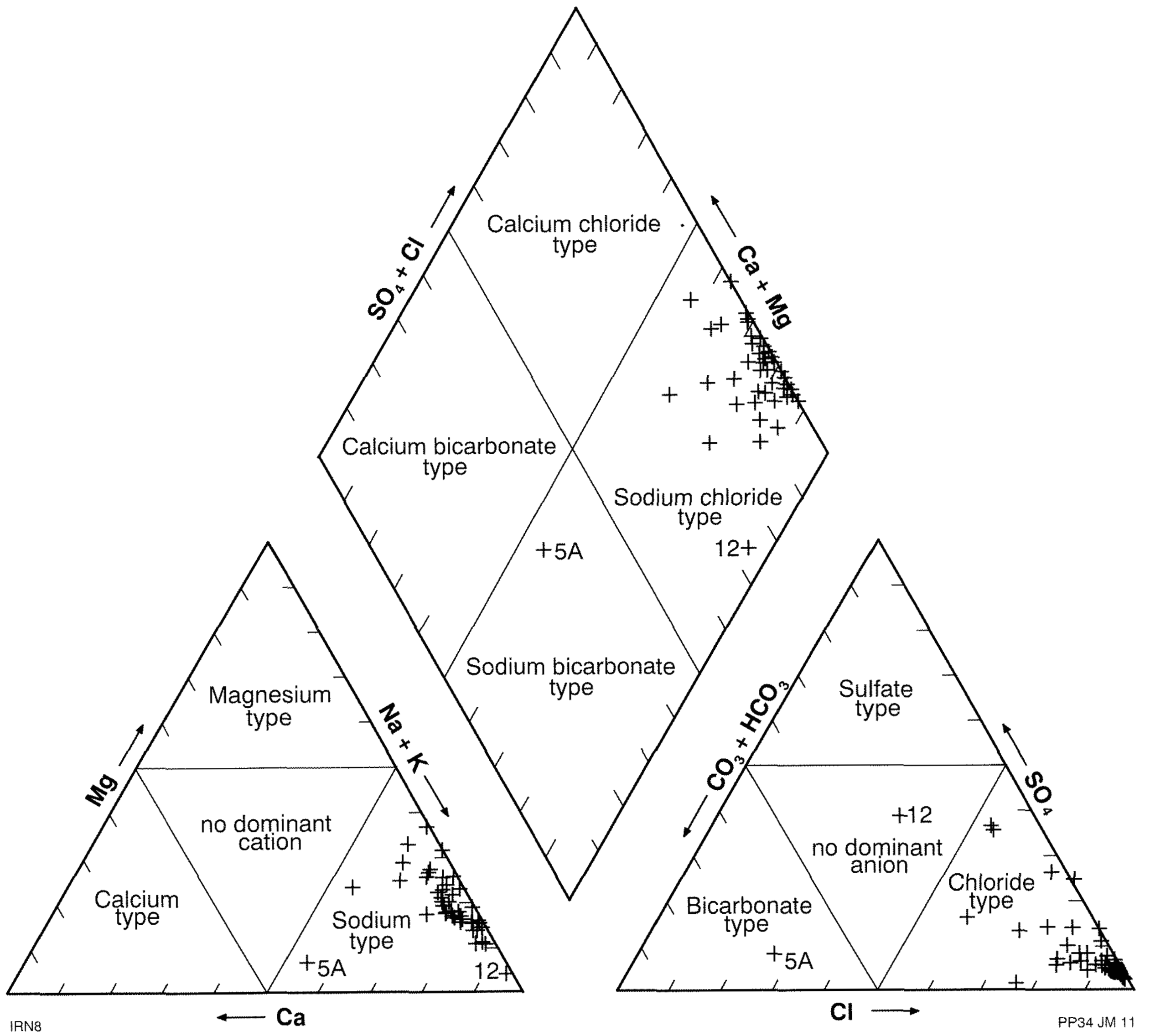


**Figure 11. Piper trilinear diagram**

watertable rests in clayey strata (CBS6, CBS10 and CBS13). The groundwater outside the basin is typically of neutral pH. CBS27 is sited alongside a swampy drainage line and contains slightly acidic groundwater (pH 5.0) as does CBS38 (pH 4.5), which is drilled in granitic rocks south of the Premier Sub-basin.

High concentrations of iron and sulfate ion (Vogwill and Brunner, 1985), and dissolved hydrogen sulfide and carbon dioxide (Hammond and Boyd, 1988), are common in groundwater from inside the basin. The groundwater is highly corrosive as a result of the acidity, dissolved gases, and chloride content.

Heavy metals were not determined but they occur in low concentrations in the basin and some are concentrated in the residues that are left after burning of the coal (Wilson and Davy, 1989) . Groundwater in the basin may contain background concentrations of these elements, particularly near ash dumps.

# Conclusions

Important fresh groundwater resources occur in the Collie Basin. The drilling program has provided new geological and hydrogeological information which, with existing data, has allowed the most detailed account of the hydrogeology to date. The study has shown that the groundwater regime reflects the complex structure and stratigraphy of the basin and that the aquifers have been greatly affected by coal mining and groundwater abstraction.

The regional watertable is now defined with reasonable accuracy and this, together with watertable monitoring, has allowed identification of areas in the basin which are affected by changes in the groundwater regime. The work has also enabled recalculation of the water balance and groundwater resources to be made. It is estimated that the basin contains about 7300 x $10^6$ $m^3$ of fresh (<750 mg/L TDS), commandable groundwater in storage, and that total recharge is 31 x $10^6$ $m^3$/year comprising rainfall recharge of about 26 x $10^6$ $m^3$/year (13% of average annual rainfall) and recharge from streams of about 5 x $10^6$ $m^3$/year.

Groundwater abstraction is estimated to be about 39 x $10^6$ $m^3$/year and thus exceeds total recharge. As a consequence the watertable in the basin is depressed over an estimated 100 $km^2$. Groundwater heads at depth are similarly affected, but over a larger area extending possibly to the basin boundary. Changes occurring within the groundwater system are also affecting stream flow, and may have other environmental consequences.

Further work, entailing deeper drilling, will be directed towards gaining a better understanding of the hydrogeology at depth in the Collie Basin.

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